" THE MECHANISM OF BOILING."

BY

RAM SURAT DUBEY, M.Sc., A.R.T.C., A.R.I.C.

A THESIS

SUBMITTED TO THE UNIVERSITY OF GLASGOW FOR THE Ph.D. DEGREE IN THE FACULTY OF SCIENCE.

APRIL, 1949.

ProQuest LLC.
789 East Eisenhower Parkway
P.O. Box 1346
Ann Arbor, MI 48106 – 1346

ACKNOWLEDGMENTS.

The author wishes to express his sincere gratitude to Prof. W. M. Cumming, O.B.E., D.Sc., F.R.I.C., M.I.Chem.E., F.R.S.E., and to Dr. F. Rumford, B.Sc., Ph.D., F.R.I.C., M.I.Chem.E., under whose supervision and able guidance these investigations were carried out.

Thanks are also due to Mr. M. Goswami, M.Sc., A.R.T.C., A.R.I.C., for his kind help in taking data on the vertical tube evaporators, and to Mr. J. M. McGowan who kindly repeated the tests on ethyl alcohol boiling over heated platinum wires.

Ram S. Dubey.

C O N T E N T S.

CHAPTER. I.

CHAPTER. II.

CHAPTER. III.

Page.

****

ABSTRACT.

Boiling has been found to depend largely upon the presence of foreign agents called ebullators, which appear to aid boiling (1) by supplying bubble nuclei in the form of adsorbed gas, and/or, (2) by creating cavities on the heat transfer surface, in which the liquid undergoes local superheating. Presence of adsorbed gas or vapour seems to be the most probable reason for nucleus bubble formation without abnormal superheating. The nature of boiling of water, ethyl alcohol,&toluene, has been observed in a glass-tube, vertical, natural-circulation, evaporator, and coefficients for the boiling section reported. The fluid column can in general be divided into boiling and non-boiling sections. Working on this basis, overall and film coefficients for the boiling section are reported for water under natural circulation in a stainless steel tube, and for water, ethyl alcohol and toluene in a copper tube under natural-circulation. The coefficients for the boiling film for water are the highest and of the same order as those obtained by

previous investigators. The same three liquids have been studied under forced-circulation in the copper-tube. The coefficients obtained are generally lower than before. Boiling has also been studied on electrically heated wires of three different diameters with water and ethyl alcohol at their boiling points, under forced-circulation at three different velocities. Forced-circulation increases heat transfer in the natural convection region, and in the boiling region for low values of temperature drop. Above about 25°F of temperature drop neither velocity nor wire diameter seem to affect the heat flux.

Latent heats have been determined at atmospheric and lower pressures for ethyl alcohol (95.6%), and toluene.

INTRODUCTION.

THE MECHANISM OF BOILING

I N T R O D U C T I O N.

Although the phenomena of the "singing kettle" and the "dancing drop" must have been familiar to man since quite early times it is relatively within very recent decades that the formation of bubbles has received scientific attention. This is partly due to the fact that the formation of a bubble is a non-equilibrium process not amenable to thermodynamic treatment. In addition, the general prevalence of extraneous bubble nuclei in aerated liquids and on ordinary surfaces which promote boiling and effervescence, has led to the lack of a realisation of the problem. However, the role which boiling and the transfer of heat to boiling liquids play in several industrial operations like steam-raising, evaporation, refrigeration, etc., marks them as one of the most important branches of Chemical Engineering.

PART. I

Types of Boiling

&

The Boiling Curve.

When water is heated on a hot surface a stage comes when bubbles begin to arise from the bottom and burst on the surface, agitating the whole mass of liquid at the same time. As the heating is continued, the boiling becomes more and more vigorous with increasing temperature difference between the hot surface and the boiling liquid. In the range of small temp. drop, Δt, up to about $5^{\circ}F$, the coefficient of heat transfer ('h', in B.Th.U/hr/sq.ft./$^{\circ}F$) and the Heat Flux ($Q/A\theta$, or, q/A, in B.Th.U/hr/sq.ft.) rise slowly with increasing temp. drop. The heat passes by free convection only and the flux and the heat transfer coeff. are of the same order of magnitude as for warming the liquid without phase change.

With increasing temp. drop, the flux and the surface coeff. of heat transfer rise quite rapidly. During this stage bubbles have been rising from selected points or 'nuclei' in neat chains and the number of these nuclei has increased gradually till, by now, the whole surface is practically covered with the latter. This is the region of " Nucleate Boiling ".

Fig. 0.1. shows nucleate boiling of CCl_4 (Ref.2, p.450) from a steam-heated tube. In the region of nucleate boiling both the flux and the heat transfer coeff. are large and of the same order of magnitude as those for condensation.

On further increasing the temp. drop, the flux and the film coeff. of heat transfer quickly attain a maximum and then begin to decrease. The surface, which was already covered with nuclei, now assumes a thin film of vapour over it. This film bulges occasionally evolving rather large flabby bubbles. This is the stage of Film Boiling. The film-boiling having set in, the flux gradually falls to a minimum and then rises steadily again with increasing Δt but the film coefficient at first falls rapidly and then more slowly. Fig. 0.2. shows the film boiling of CCl_4 on the same surface as in Fig. 0.1.

Fig. 0.3., known as the Boiling Curve, shows qualitatively what happens when the temp. drop is increased from a very small Δt to a very high value. The point of inflexion in the curve for flux, $Q/A\theta$, which marks the transition between nucleate and film boiling, corresponds to the maximum flux attainable in the range of 'nucleate' boiling, and the temp. drop at which this inflexion occurs, in the curve for flux, is called the Critical Temp. Difference.

For water this maximum is as large as 400,000

(a). Nucleate boiling of carbon tetrachloride (b.p. 76.8° C.). Heating surface: Steam-heated ¼" O.D. steel tube. Exposure: 1/195 sec.

Fig. 0.1.

Film boiling of carbon tetrachloride (b.p. 76.8° C.). Heating surface: Steam-heated ¼" O.D. steel tube. Exposure: 1/50 sec.

Fig. 0.2.

Figs. 0.1 and 0.2 above have been taken from Ref. 2, Pp. 450 and 452, respectively.

B.Th.U/hr/sq.ft. and the corresponding Critical Δt is $45^{\circ}F$ (Ref.3,p.297).

The first complete Boiling curve was given by Nukiyama (J.Soc.Mech.Engrs., Japan, 37,367,1934; cited by Refs.2,3,and6). Farber and Scorah[7], using electrically heated Ni, W, and Chromel A and C wires, found that different metals give different boiling curves for the same liquid. When water was boiled at different elevated pressures, the same metal gave different boiling curves. However, throughout their experiments the general form of the curve remained the same. McAdams et al[6], using electrically heated platinum wires of four different diameters, took data on heat flux in the film boiling range well above the maximum possible in thee nucleate range. Film boiling appeared to destroy active nuclei and a small time lag was observed after a decrease in Δt from the film boiling range before nucleate boiling again became active. As the wire diameter increased the maximum flux for nucleate boiling increased to a maximum, the corresponding Δt remained constant, and the heat flux at the incidence of film boiling decreased. Some tests at higher pressures resulted in extremely high heat fluxes.

It is by no means certain that all the variables with an important effect on the shape and the position of the boiling curve are known. The most significant, as far as is known at present, is the character of the heating

surface, although it is impossible to draw conclusions as to the effects of specific changes in the surface. Corrosion films, surface tension and the concentration of dissolved solids affect the whole curve. In a general way, the curve is shifted to the right by an increase in either variable.

Critical Δt and Film Boiling

The Critical Δt differs for each surface-liquid pair[1,3 (p.315),4,5,16], and can be shifted somewhat by various treatments of the heating surface and by the addition of a wetting agent to the liquid. Between the maximum and the minimum points of the boiling curve for heat flux, there exists " Mixed Boiling " - nucleate boiling on some parts of the surface and film boiling on the rest- and true film boiling does not set in until the minimum point has been passed. In the range of true film boiling, radiation, even at the highest temperature level, can account for only 10-12% of the heat flux. Hence, heat transfer across the vapour layer must be largely by conduction and convection.

In the range of mixed boiling, just after passing beyond the Critical Δt, the flux and 'h' begin to decrease because of the formation of a film of vapour of low thermal conductivity that insulates the heating surface

from the liquid. This phenomenon was first mentioned by Leidenfrost in 1756 (cited by Ref.2 and 3) who observed that drops of water evaporate more slowly on a red-hot surface than on a considerably colder one. On the former the drop assumes the " Spheroidal Form " and is separated from the heating surface by a film of vapour on which it dances about. If the surface is gradually cooled, a point comes when the drop boils off almost explosively. The spheroidal state is a non-equilibrium condition assumed by two or more bodies of solid or liquid, when an attempt is made to bring them together while their temperatures differ by more than a determinate amount; it is characterised by the subsistence of a layer of vapour between the bodies, which resists and prevents their being brought together into direct contact. Evidently, film boiling is an instance of the spheroidal state. Although with drops there is no bubbling, this behaviour is essentially analogous to that in boiling when the critical temperature difference is approached from the high side. Attempts have been made to measure the minimum Δt for which the drop assumes the spheroidal state, but the experimental technique was such that the results probably have little precision. The data of Boutigny and Berger (cited by Ref. 2) show that the maximum surface temperature for the spheroidal state in the case of a given liquid depends on the kind of hot surface.

The critical Δt is best determined by finding the maximum flux with a vapour-heated surface. The Crit. Δt for a given surface-liquid pair is substantially independent of the boiling temperature and the corresponding total pressure, and the corresponding flux increases with increase in the boiling temperature.

However, Moscicki and Broder (cited by Ref.2) used an electrically-heated wire to find the crit. Δt, and the temp. at which the wire was burnt out or showed a sudden increase in temperature was taken to indicate the point of inflexion between nucleate and film boiling. They found the limiting temp. of the surface to be independent of the main body temperature of the liquid. This seems to indicate that the limiting factor is primarily the temperature at the heating surface-liquid interface. Up tp the point of failure of the heating wire, the fluid immediately adjacent to its surface would, in all cases, be at the temperature of the latter and the only change in local conditions caused by the lowering of the main body temp., would be a steepening of the temp. gradient in the liquid. Hence the flux per se is without influence and the critical Δt should be understood as merely a temp. measured relative to the boiling point.

Ref.3 (p.310) gives a table of results on Crit.

temp. drop obtained by various investigators for a large number of surface-liquid combinations and different boiling points of the same liquid. For a given liquid and pressure, the critical Δt is increased by substantial deposits of scale and is less for dropwise than for film condensation of steam.

The crit. Δt at which the maximum flux occurs, is sometimes even less than the difference between the temperature of atmospheric steam and the boiling point of the liquid in question. Hence, cases in practice can and do arise in which turning on more steam will reduce the capacity of the equipment for boiling. It seems probable that, at the maximum, the temperature of the heating surface is identical with the temp. for the occurrence of the spheroidal state with the surface-liquid system in question. If not identical, the two temperatures must be nearly the same because for temperature differences slightly beyond the Crit. Δt the system has definitely assumed the spheroidal state.

****

Mechanism of Nucleate Boiling.

The most comprehensive published study of bubble formation is that due to Jakob[9] and his associates. If a liquid and its vapour exist together, with no exchange of heat between them, then it is a condition of equilibrium, with equal number of molecules being exchanged between the two phases. In the process of evaporation true equilibrium does not exist, since heat and mass are being continuously transferred from one phase to the other.

The problem arises of the forces which control bubble formation. The formation of a liquid-vapour interface requires energy and energy is required to extend the surface once formed. For a given increase in volume a greater percentage increase in surface area occurs with a small, newly-formed bubble than with a large bubble. Thus, there is a high natural resistance to the origin of a bubble. This surface energy requirement accounts for the fact that the vapour pressure inside the bubble is lower than would normally occur for the same temp. and pressure condition of the environment. Thus, according to Lord Kelvin,

$$p_c = p_s - \frac{2\sigma}{R} \cdot \frac{\rho'}{\rho' - \rho''} \quad \cdots \quad \cdots \quad (0.1)$$

where p_c = saturation pressure at concave surface,

p_s = " " " plane "

σ = surface tension,

R = Radius of bubble,

ρ' = Density of saturated fluid and

ρ'' = ,, ,, ,, vapour.

At the same time the other effect of surface tension is that for a bubble,

$$p_{in} = p_{ex} + \frac{2\sigma}{R} \quad \ldots \ldots \ldots \quad (0.2)$$

where, p_{in} = pressure in the interior of the bubble, and

p_{ex} = ,, on ,, exterior ,, ,, ,, .

Both the above relationships require the liquid to be superheated in order that origin and development of bubble may take place. For, unless there were a temp. gradient, no evaporation into the interior of the bubble would take place.

The importance of this superheat was first recognised by Bosnajakovic' [Tech. Mech. und Thermodynamik (1930), Vol.I, p.358]. Since the nucleus bubble is infinitely small, Equations (0.1) and (0.2) would require excessive superheating. In fact, such superheating has been observed with pure liquids. [27, 29.]

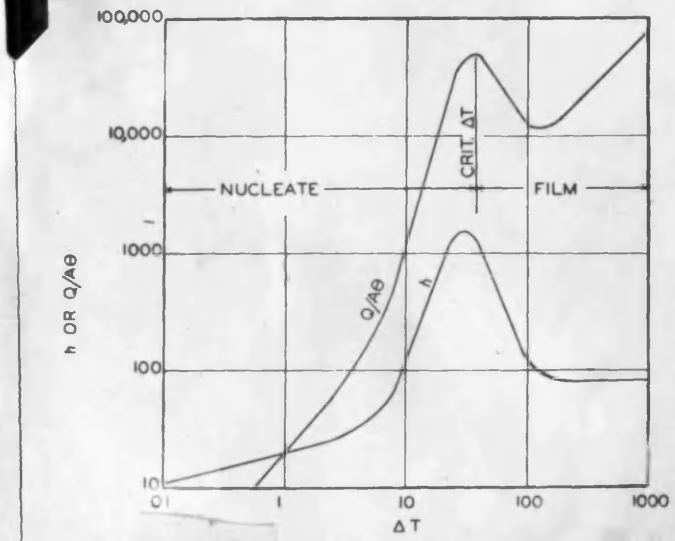
Actually, however, there are often nuclei present which facilitate the formation of the nucleus bubble. After "an explosion on a microscopic scale" the bubble comes into

existence and the superheat provides the motive force to its divelopment.

By means of stroboscopic and cinematographic photography, Jakob and his associates made a detailed study of the production, rate of rise and growth of bubbles. Bubbles are formed at the average rate of 20/sec.; they adhere to the surface for 1/40 th of a sec. and then detach themselves; the point is slightly cooled by water and reheated, and, after another 1/40 th of a sec., the next bubble originates.

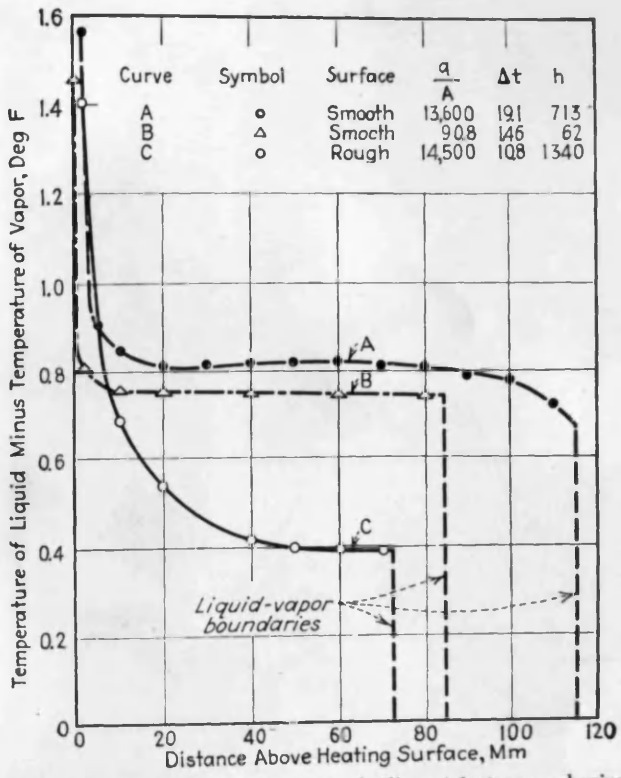
The Distribution of Temp. above the Heating Surface upto the steam region has also been cleared up by Jakob. (Fig. 0.4). The temp. changed suddenly at the water level surface from the somewhat higher temp. of water to the saturation temp. of vapour, this being true in the entire steam space. The mean superheating of water changes but little with the speed of evaporation. It is 0.5 ^{o}C for a smooth and 0.3^{o}C for a rough surface.

In the close proximity of the heating surface the superheating of water increases greatly upto the temp. of the heating surface, indicating that a thin layer apparently exists, not mixed by convection similar to the well-known Prandtl Boundary Layer. In contrast to the temp. drop at the water level surface, the temp. drop in this layer depends on the heat flow, rising with it. The temp. drop is



Typical Boiling Curve.

Fig. 0.3 (Taken from Ref. 2, Page 469).



—Temperature explorations in water boiling at 1 atm on a horizontal plate.

Fig. 0.4. (Taken from Ref. 8, P. 299).

greater in the case of a smooth surface than in the case of a rough one. Thus roughness facilitates heat transfer by supplying a large number of nuclei for bubble formation. These bubbles create a better convection and hence less superheat in the liquid. Since bubbles originate in the thin layer at the heating surface, they are exposed to a hotter environment, a factor favourable to their growth.

THEORIES OF SUPERHEATING AND SUPERSATURATION AND THE ROLE OF EBULLATORS IN BUBBLE FORMATION

Relatively little has been published dealing with the formation of a bubble of vapour in a superheated liquid and the escape of gases from supersaturated solutions. This is due partly to the fact that bubble formation is a non-equilibrium process not amenable bo thermodynamic treatment. In addition general prevalence of extraneous bubble nuclei in aerated liquids and on ordinary surfaces which promote boiling and effervescence has led to a lack of realisation of the problem. However, there are several problems in Chemical Engineering where bubble formation is desired, and there are others in hydraulics and pressure physiology where bubble formation is to be avoided if possible.

The problem of the effervescene of a liquid supersaturated with gas is strictly analogous to the problem of bubble formation in superheated liquids or liquids under

negative pressure. Just as a liquid can be superheated under a given pressure, so under a given temp. the pressure can be reduced or even made negative so that a tension develops in the liquid.[11,12,13,14,15] In all these cases, however, a foreign nucleus initiates bubble formation without a resort to such extreme conditions.

The fundamental difficulty of bubble formation lies in the surface tension of the liquid.

Surface Tension & the Bubble - A molecule in the interior of a liquid is attracted equally in all directions. On a molecule in the surface, however, there is a resultant attraction inwards because the number of molecules per unit volume is greater in the bulk of the liquid than in the vapour. As a consequence of this inward pull the surface of a liquid always tends to contract to the smallest possible area; it is for this reason that drops of liquids and bubbles of vapour in a liquid become spherical, the surface being then a minimum for a given volume. In order to extend the area of the surface it is obviously necessary to do work to bring the molecules from the bulk of the liquid into the surface against the inward attractive forces; the work required to increase the area by 1 sq.cm. is called the Free Surface Energy. The tendency for a liquid to contract may be regarded as a consequence of its possession of free energy, since approach to equilibrium is always accompanied by a diminution of free energy: -

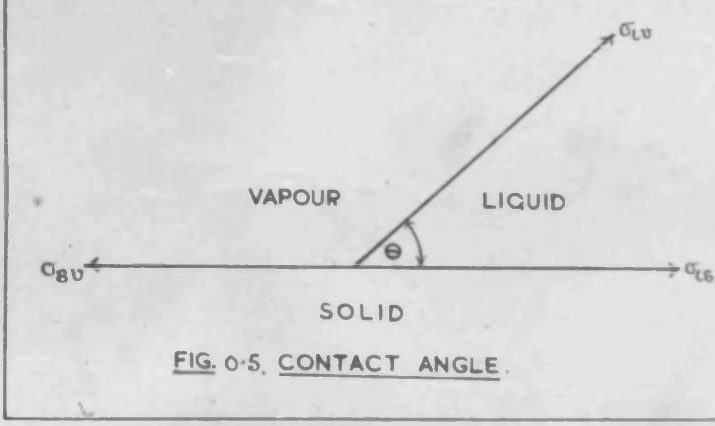
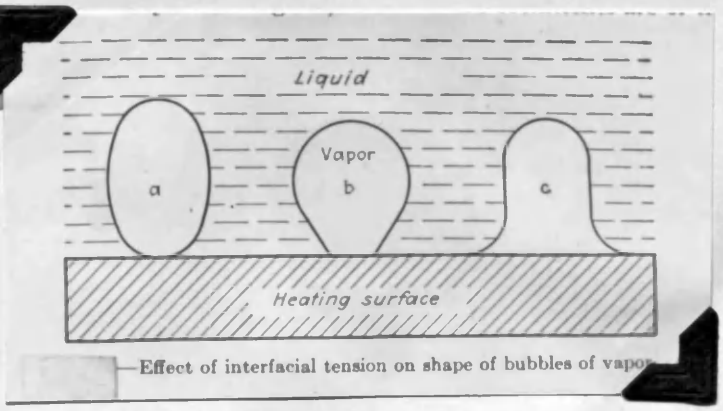


FIG. 0·5. CONTACT ANGLE.



Effect of interfacial tension on shape of bubbles of vapor

Fig. 0.5a. (Taken from Ref.3, P.301.)

$$[\Delta F]_{T,P} \leq 0 \quad \ldots \quad \ldots \quad (0.3)$$

As a result of the tendency to contract, a surface behaves as if it were in a state of tension. This tension or force is uniform over the whole surface and its magnitude in dynes acting at right angles to any line of 1 cm. length in the surface is called Surface Tension. To extend such a surface under tension requires energy. The work done in extending the area of the surface by 1 sq.cm. is equal to the surface tension, which is the force per cm. opposing the increase, multiplied by 1 cm., the distance through which the point of application of the force is moved. It follows, therefore, that the surface energy in ergs/cm.^{2} is numerically equal to the surface tension in dynes/cm. Both surface tension and surface energy have the same units, viz., mlt^{-2}, and so the quantities are mathematically identical. The symbol "σ" will be used to denote either of them.

This tension in the surface is dependent on the nature of the two substances in contact. Consider the case of a vapour bubble in a liquid, in contact with the solid surface. (Fig.0.5), having a Contact Angle, θ.

For equilibrium, the forces that come into existence must balance.

$$\therefore \sigma_{sv} = \sigma_{lv} + \sigma_{ls} \cos\theta \quad \ldots \quad \ldots \quad (0.4)$$

If an imaginary cylinder of unit cross-section is ruptured to produce two unit liquid-vapour surfaces, the

work done, called the Work of Cohesion,

$$W_l = 2\sigma_{lv} \quad \ldots \quad \ldots \quad \ldots \quad (0.5).$$

If the process involves forming a vapour phase on an already existing solid-liquid interface, two new surfaces are formed while the third disappears, the process requiring the Work of Adhesion which is given by

$$W_{ls} = \sigma_{lv} + (\sigma_{sv} - \sigma_{ls}) \quad \ldots \quad \ldots (0.6)$$ [Dupré Equn.]

where, $(\sigma_{sv} - \sigma_{ls})$ is called the Adhesion Free Energy.

From (0.4) and (0.6),

$$W_{ls} = \sigma_{lv}(1 + \cos\theta) \quad \ldots \quad \ldots \quad (0.7)$$

or,
$$\cos\theta = \left[\frac{W_{ls}}{\sigma_{lv}} - 1\right] \quad \ldots \quad \ldots \quad (0.8)$$

$\therefore$ From (0.5) and (0.8),

$$\cos\theta = \left[\frac{2W_{ls}}{W_l} - 1\right] \quad \ldots \quad \ldots \quad (0.9)$$

Showing that the contact angle, θ, depends upon the relative values of the Work of Adhesion and the Work of Cohesion of the liquid, i.e., upon the relative attraction of the solid and liquid, and between the molecules of the liquid itself.

Wetting of a solid by a liquid (See Fig.0.5a) is, therefore, the result of a relatively high degree of attraction between the molecules of the solid and the liquid ($\theta < 90^\circ$)

and has now been recognised as an important factor in heat transfer. If the Adhesion Free Energy is a measure of wettability, a negative value would be called in contrast, the "Repulsion Free Energy", corresponding to $\theta > 90^{\circ}$.

Total Energy of a lb. of a mixture of vapour bubbles & Liquid :- When two phases of a substance exist together, the interfacial energy is given by

$$u_{int} = \left[\sigma - \frac{T\,\delta\sigma}{\delta T}\right] A \qquad \ldots\ \ldots\ (0.10)$$

$T\left(\frac{\delta\sigma}{\delta T}\right)$ is the latent heat required to maintain the temp. when area A is extended; σ is the potential energy or surface tension. This interfacial energy is negligible when the surface is plane. But in the case of a mixture of vapour bubbles and liquid it is considerable. In such a case the interfacial area, A, would be $[4\pi r^2 n]$ and volume V would be $\left[\frac{4}{3}\pi r^3 n\right]$, n being the number of equal size bubbles, and r the radius. The weight $\propto$ "x" of vapour would be $\frac{V}{v}$, where v is the sp. volume. The total interfacial energy would, then, be

$$u_{int} = \frac{A\left(\sigma - T\frac{\delta\sigma}{\delta T}\right)}{x} = \frac{3\left(\sigma - T\frac{\delta\sigma}{\delta T}\right) v}{r} \qquad \ldots\ \ldots\ (0.11)$$

The total energy of a lb. of such a mixture would be given by $u_t = x u_g + y u_f + A\left(\sigma - T\frac{\delta\sigma}{\delta T}\right)$

where x and y are vapour & liquid fractions, and

u_t = total internal energy of a lb. of mixture,

u_g = internal energy of saturated vapour / lb.

u_f = " " " saturated liquid / lb.

Since $x+y=1$,

$$u_t = x u_g + (1-x) u_f + A\left(\sigma - T\frac{\delta\sigma}{\delta T}\right).$$

or,
$$u_t = u_f + x(u_g - u_f) + A\left(\sigma - T\frac{\delta\sigma}{\delta T}\right)$$

$$= u_f + x u_{fg} + A\left(\sigma - T\frac{\delta\sigma}{\delta T}\right) \quad \ldots \quad \ldots \quad (0.12)$$

where,

$$u_{fg} = u_g - u_f$$

= internal latent heat per lb.

Since all bubbles have been assumed equal size, from (0.11) and (0.12), we get

$$u_t = u_f + x\left[u_{fg} + \frac{3\left(\sigma - T\frac{\delta\sigma}{\delta T}\right)v}{r}\right] \quad \ldots \quad \ldots (0.13)$$

which indicates that the latent heat required would be increased by the interfacial energy, of which $x(v\sigma/r)$ is the free surface energy. Knowing σ, v and r, this could be calculated. The specific volume of vapour to use would not be the specific volume of the vapour as listed in tables, which is for bubbles of infinite radius, but rather that vapour at the pressure within the bubble which, for small bubbles, according to the capillary theory (see eqn. 0.2) would be very high. The density of such bubbles would approach that of the liquid.

This mixture considered here would represent an unstable state which, in the absence of some stabilising restraint, would change by bubble coalescence to a more stable state possessing smaller interface, the nearest approach to the plane surface. The interfacial energy would be reduced to a minimum value and this energy released would effect further vaporisation.

EBULLATORS:-

Various solids like glass beads, porous ~~porous~~ porcelain, glass-wool, etc., which are generally used for obtaining smooth boiling without considerable superheating are called ebullators. It is probable they might be acting by modifying these energy relationships that come into play when interfaces are created.

Larson[10] attempted to explain the role of ebullators by correlating the adhesion free energy of various surface-liquids combinations with the ease of bubble formation. At any particular temperature which alone governs the magnitude of surface tension of liquids, $2\sigma_{lv}$ represents the free interfacial energy that must be available if boiling or equilibrium is to occur. When accurate measurements of σ_{lv} are made a glass capillary of sufficiently small size is used and θ is assumed equal to zero. The capillary rise (the increase in potential energy) corresponds to the work of separation.

$\therefore$ Capillary rise $= W_{ls} = \sigma_{lv} + (\sigma_{sv} - \sigma_{ls}) = 2\sigma_{lv}$ ... (0.1

Now values of σ_{lv} are either known or can be experimentally determined and hence the maximum energy of the interface when $\theta = 0$, could be calculated. An ebullator, however, is supposed to supply all or a part of this energy, depending on θ. Since $2\sigma_{lv}$ is the energy required in the absence of the ebullator or even in the presence of one with a contanct angle $\theta = 0$, the energy supplied by the ebullator would be equal to $[\sigma_{lv} - (\sigma_{sv} - \sigma_{ls})]$ and an energy equal to $[\sigma_{lv} + (\sigma_{sv} - \sigma_{ls})]$ would have to be supplied in the form of superheat.

By finding the degrees of superheat both in the absence and in the presence of the ebullator, the energies of free surface formation for the two cases could be found from a knowledge of σ_{lv} at the two temperatures. The difference in the two values of σ_{lv} would correspond to $[\sigma_{lv} - (\sigma_{sv} - \sigma_{ls})]$ supplied by the solid. If, for example, $\theta = 90^{\circ}$, the adhesion free energy would be zero and boiling should begin immediately on heating the saturated liquid at constant pressure. Working on this basis, Larson tested a large number of solids for their ability to assist boiling. Preliminary tests with water showed that ebullition could be correlated with floatability, and appreciable differences in this property were noted. Physical roughness did not appear to be a factor nor did the porous nature of the substance. Silica gel became inactive after adsorbed air was dissipated. Sharp points were not necessrily nuclei in as much as broken glass or silica sand did not pro-

mote boiling. Tests were also made with hydrocarbon liquids. In general, substances known to be non-wetted proved to be good ebullators.

To measure the ebullating characteristics quantitatively, an attempt was made by Larson to find the maximum amount of liquid superheat which each substance would permit. The results varied from 112°F to 288.5°F, the normal boiling point of water being 211°F. A number of tests were conducted without an ebullator other than the glass apparatus itself. These gave a scattering of test results varying from 249°F to 288.5°F. Temperature measurements were not precise.

Tomlinson (cited by Ref. 32) also showed that sharp edges and points do not promote bubble formation as commonly held. Dorsey (Phys. Rev., 55, 594, 1939) pointed out that edges and points which were wetted by water could not act as bubble nuclei. Dean[32] and his co-workers confirmed this conclusion whereas Cassel considers surface roughness so important.

Larson came to the conclusion that ebullition does depend on the presence of an ebullator whose property assumed to be the adhesion free energy, determines the amount of superheat tolerated. Since the minimum temperatures for various substances to initiate a bubble in water were sometimes as low as 112°F , it seems probable that adsorbed gases and those produced chemically must have vitiated results. The formation of bubbles below the normal boiling point goes

against the capillary theory.

The behaviour of wetting agents might also be explained by their ability to modify interfacial tensions, resulting in the lowering of the adhesion free energy.

To explain bubble formation in the absence of an ebullator, Döring (cited by Refs. 27 & 32) considers the growth of minute spherical bubbles containing 1, 2, 3, .., n, vapour molecules, 'n' being the critical size above which alone these initial bubbles are stable. The number of such bubbles as survive above this critical size varies sharply with temperature. Calculations based on this theory show that at 142°C ether may give 1 bubble per sec. but at 143°C it will give 10^5 bubbles per sec., showing that at this temperature the liquid is very unstable. This result agrees with the experiments of Wismer[28] et al who found that water saturated with CO_2 or O_2 at 14 - 30 atmospheres and suddenly decompressed to 1 atmos. showed no immediate bubble formation, and bubble formation occurred after a few seconds only when the temperature was raised to about 70°C. With N_2, under more than 100 atmos., on decompression, bubbles formed only on the surface. These experiments strongly support the view that only at very high pressures is the spontaneous formation of bubbles possible.

Various attempts have been made to ascertain the

maximum temperature to which a pure liquid may be heated without causing it to boil[10, 28, 29]. Eggleton and Kermack[27] give a table of the highest temperature and the corresponding vapour pressure ~~before~~ maintained for 5 seconds with a number of liquids before boiling commenced.

The phenomenon of liquids existing unbroken under negative pressure has been demonstrated. J. Meyer (cited by Refs. 10,27 & 32) found that the breaking tension of ethyl ether at room temperature was at least 72 atmospheres. Dixon [Proc.Roy.Soc.,Dublin, NS 14, 229 (1914)] cooled water in a sealed tube. The liquid did not break away from the walls until pressure inside the tube was minus 150 atmos.

With the help of the above theory Döring gave the tensile strength of ether at 20°C as 352 atmos., far higher than that reached by Meyer experimentally. This might have been due to imperfections in the experiments of the latter.

A second theory has been formulated by Fürth (Proc.Cam.Phil.Soc., 37, 252-276, 1941) in the course of a general theory of the liquid state. An ordinary gas is very largely an empty space with here and there a molecule. A liquid consists of fairly densely crowded molecules, with here and there an empty space, or, 'hole'. Fürth concentrates attention on the holes in the liquid rather than on

the liquid itself and this makes possible a statistical theory of liquids rather similar to the ordinary statistical theory of gases. The holes, which are considered to be spherical, are of all possible sizes but the majority are in the neighbourhood of the average size. It turns out that when the temperature is sufficiently low, the curve which represents the frequency distribution of holes as a function of the radius of the hole, rises to a maximum, then falls to a minimum, which may be nearly zero, and then rises again. The existence of this minimum is interpreted to mean that a growing hole has very little chance of reaching the final rising part of the curve, i.e., of developing into a large, visible, vapour bubble. When, however, the temperature is raised so that the vapour pressure is sufficiently high, then the minimum in the curve disappears and the curve now rises continuously. The liquid is then in a state of complete instability, and the temperature at which the minimum disappears is taken as the maximum temperature of superheating. The minimum also disappears if the external pressure is reduced or made sufficiently high in the negative sense. The smallest negative pressure, for which the curve has no minimum, is regarded as a measure of the maximum tensile strength of the liquid.

Fürth also applies his theory to explain the pheno-

mena connected with the escape of a gas from a supersaturated solution, in the form of bubbles. He considers only cases in which the vapour pressure of the liquid is so low that it can be neglected in comparison with the gas pressure. If the degree of supersaturation is considerable, the small quantity of gas which escapes from the system before the bubble reaches its critical point will not much decrease the concentration of the dissolved gas, which can, therefore, be regarded as constant. The theory then requires little change to give the finite external pressure , positive, or if necessary, negative, at which a finite bubble will form; it is only necessary to replace the vapour pressure by the pressure of gas in equilibrium with the dissolved gas.

Dean[32] was able to inactivate nuclei by suitable treatment and experimented on a large number of substances differing widely in their physical and chemical characteristics. When the nuclei became inactive, bubble could be initiated by mechanical shock. Hatcher and Sage (Ind. Eng. Chem., 33, 443, 1941) showed that turbulence reduced supersaturation in hydrocarbon mixtures and suggested that localised regions of low pressures associated with vortices, which are widespread in turbulent motion, are conducive to the formation of small bubbles. To explain bubble formation by mechanical shock, turbulent motion, and ultrasonic

waves, etc., when active nuclei (which according to Dean are invariably supplied by adsorbed air or gas) had become inactive, Dean extended this hypothesis and suggested that free vortex motion is probably always responsible for the bubble formed when liquids are subjected to mechanical shock or disturbance. Assuming a spherical bubble, the pressure inside it at the centre of a free vortex is given by

$$P = (-\tau d/8\Pi^2 r^2) + \frac{2\sigma}{r} \quad \ldots \quad \ldots \quad (0.15).$$

where

P = Pressure difference between the point in question and the undisturbed liquid, neglecting hydrostatic pressure;

τ = Circulation;

d = Density of the liquid, and

r = Radius vector of the point in question.

In order that the bubble may survive, P must be large enough to overcome total imposed pressure.

This interpretation has been supported qualitatively by experiments. A practical conclusion from this theory is that bubbles can always be produced by active stirring or by turbulent motion of the liquid - as in violent convection.

Cassel's Theory:-

The vapour pressure, p_{in}, of a concave liquid surface is smaller than that of a plane surface, p_o, of the same liquid at the same temperature by an amount given by Equation (0.1) which can also be put in the following form :-

$$p_{in} = p_o \exp -(2\sigma M/rDRT) \quad \ldots \quad (0.16)$$

where

$\frac{M}{D}$ = Mole volume of the liquid.

The only means of satisfying Equations (0.2) and (0.16) is by superheating the liquid with regard to the external vapour phase. The temperature required can be determined if vapour pressure as a function of temperature is known. This relation is given by the Clausius-Clapeyron Equation integrated over a reasonable temperature range:-

$$\log p_o = \log p_{ex} + L\,(T-T_o)/RTT_o \quad \ldots \quad (0.17)$$

where L = Molal Latent Heat of Vaporisation and where it is assumed that the ideal gas law holds for the vapour phase. By eliminating p_o,

$$p_{ex} + \frac{2\sigma}{r} = p_{ex} \exp \frac{L\,(T-T_o)}{RTT_o} = \frac{2\sigma M}{rRTD} \quad \ldots \quad (0.18)$$

which represents the correlation of the temperature of superheating and the size of the bubble in equilibrium with

the liquid at that temperature. In developing the exponential and neglecting all but the first term, we may write, as a second approximation :

$$\frac{2\sigma}{rp_{ex}} \cong \frac{L\,(T-T_o)}{RTT_o} - \frac{2\sigma M}{rRTD} \quad \ldots \quad \ldots \quad (0.19)$$

From this the excess temperature necessary for the existence of a bubble of radius 0.001 cm. in water boiling under atmospheric pressure is 0.32°C and, under a pressure of 10 atmos. (200 lbs./ sq. in.) at 195°C only about 0.03°C.

The Thomson term, $2\sigma/rRTD$, plays only a minor role of correction except when r approaches the dimensions of the water molecule.

These considerations refer to the equilibrium of a bubble within a superheated liquid. This equilibrium, however, is unstable. In view of M. v. Smoluchowski's (Ann. d. Physik., 25, 205, 1908) work on the kinetic theory of matter, heterophase fluctuations must be expected within the saturated of superheated liquid. Such a liquid has to be considered as an emulsion within which bubbles of all sizes are dispersed according to a statistical distribution. According to the laws of statistical mechanics, the number of bubbles with the critical diameter given by equation (0.19) and having the greatest chance of contributing to the phenomenon of boiling is given by

$$B = C \exp\,(-W/kT)$$

where W is the activation energy.

The following expression gives the rate of nucleus bubble formation in units/cc./sec,

$$-\frac{dB}{dt} = \frac{C}{2\tau} \exp(-W/kT) \quad \ldots \quad \ldots \quad (0.20)$$

which can be checked experimentally, τ being the mean life time of the nucleus bubble.

Eliminating the radius of the globular mass by means of the expression $2\sigma / r = p_o - p_{ex}$,

$$W = \frac{16\ \Pi\ \sigma^3}{3k(p_o - p_{ex})^2} \quad \ldots \quad \ldots \quad \ldots \quad (0.21)$$

With rising temperature σ decreases and the denominator of (0.21) increases, so that, the exponential in (0.20) must be expected to increase rapidly within the narrow temp. range where the rate of bubble formation becomes observable.

Now according to Gibbs

$$W = \tfrac{1}{2} V (p_{in} - p_{ex}) \quad \ldots \quad \ldots \quad (0.22)$$

where V = nucleus bubble volume.

The pressure difference, $(p_{in} - p_{ex})$, being fixed by the operating conditions,(T and p_{ex}), determines the radius of the critical bubble, no matter what the value of the contact angle. But the volume of the possible bubble attached to the solid surface will be the smaller as the greater a part of the full sphere is cut off by the solid body. For instance, if the contact angle is 90^o, the nucleus

forms a half sphere, requiring only half the work given by (0.22). The larger the contact angle, the larger is the volume of the bubble subtended by the solid. When $\theta = 180^{\circ}$, $W = 0$, indicating a minimum of superheating to keep the water boiling.

These considerations apply to perfectly smooth, plane surfaces. Natural or artificial roughness of heating surfaces may substantially change conditions. Jakob[9] has definitely established that greater roughness facilitates evaporation with lesser mean temperature of superheating.

This roughness might be helping by providing a "conical dip" or a " conical tip " which may be effective in reducing nucleus bubble volume by subtending a part of it. The suspended particles to be active must be large in size. No experimental support was sought to support this theory.

Larson's Thermodynamic Theory of Bubble Formation[10]:-

The above discussions point out that liquids are likely to superheat unless a liquid-vapour interface is already present or unless an ebullator (assumed a solid) is present, whose contact angle is 90° or more, or whose adhesion free energy is zero or negative. Contact angles are difficult to measure; furthermore solid surfaces will be heterogeneous in this respect.

When bubble formation in a superheated liquid occurs, the transformation from the superheated or the metastable state to a more stable state is rather explosive and spontaneous, during which an interface must be created. To accomplish this change, it is postulated that the system passes through an intermediate momentary unstable state, a mixture of liquid and small bubbles, from which it can pass to the final equilibrium mixture state represented by a minimum phase interface. This would require that the ebullition process consist of three steps :-

(1) superheating of liquid,

(2) transformation where the interface is created, assumed to take place adiabatically and reversibly, and

(3) the dissipation of the high interfacial energy and subsequent expansion as the bubbles coalesce and grow.

To accomplish this process the system will pass through 5 stages :-

(1) Initial liquid at pressure p_2;

(2) Saturated " " " " "

(3) Superheated " " " "

(4) Dispersed vapour bubble mixture arising from state (3); and

(5) The final stable equilibrium mixture state.

State (3) is metastable and (4) unstable (its entropy

assumed to be that of 3). The change (3) to (4) involves the formation of a new phase at the expense of some of the liquid phase.

The free energy, (u - Ts), of (2) and (5) are equal; (3) and (4) are states of greater free energy by amount $_2(u - Ts)_3$ for state (3) and by '$A\sigma$' for (4). This increase of free energy could originate only from the same source ; heat absorbed is $_2h_3$; hence they are assumed equal and equivalent. (h = enthalpy; s = entropy).

$$\therefore \; {}_2(u - Ts)_3 = A\,\sigma_{1v} = \frac{A}{2} \times 2\sigma_{1v}$$

If 'n' bubbles of radius 'r' are formed,

$$A = 4\,\Pi\, r^2 n = \frac{{}_2(u - Ts)_3}{\sigma_{1v}}$$

As a further consequence, $_2(Ts)_3$ will represent the latent heat required for vaporisation in the form of n bubbles whose total volume V would not depend upon the surface energy but rather on the bulk energy. Thus:

$$\frac{V}{v} = \frac{{}_2(Ts)_3}{u_{fg}} \; ; \quad V = (4\Pi\, r^3 n)/3 = \frac{{}_2(Ts)_3 \cdot v}{u_{fg}} \; ,$$

where u_{fg} is the internal bulk latent heat and v is the volume per lb. of bubbles as initially formed. Dividing volume by area :

$$r = \frac{3v}{A} \cdot \frac{{}_2(T_s)_3}{\frac{{}_2(u-T_s)_3}{2\sigma_{lv}}} = \frac{3{}_2(T_s)_3 \cdot v\,\sigma_{lv}}{u_{fg}\,{}_2(u-T_s)_3} \quad \ldots \quad (0.23)$$

which gives the size of the nucleus bubble in the absence of an ebullator.

With a solid ebullator, the amount of superheating (and hence the increase in the free energy) would be governed by the adhesion free energy, $(\sigma_{sv} - \sigma_{ls})$. In the above expression (0.23), $2\sigma_{lv}$ would be replaced by $[\sigma_{lv} + (\sigma_{sv} - \sigma_{ls})]$, giving

$$r = \frac{3{}_2(T_s)_3 \cdot v\,(\sigma_{lv} + \sigma_{sv} - \sigma_{ls})}{2{}_2(u-T_s)_3\,u_{fg}} \quad \ldots \quad \ldots \quad (0.24)$$

This assumes that the adhesion free energy is known or could be estimated. Also, the adhesion latent heat or the heat of wetting would have to be considered as modifying u_{fg}. Also, if a dissolved gas were to act as an ebullator, the latent heat of solution would have to be considered as well.

The added bulk energy, ${}_2(u - T_s)_3$, corresponds to the adhesion free energy, $(\sigma_{sv} - \sigma_{ls})$, and for small values is proportional to the internal energy, ${}_2u_3$; the estimation is made as follows :-

$$(\sigma_{sv} - \sigma_{ls}) = \sigma_{lv} \times \frac{{}_2u_3}{u_{fg}} \quad \ldots \quad \ldots \quad (0.25)$$

Using the absolute values of the entropy in the calculations, the value of $r = 0.28 \times 10^{-9}$ ft. at 260°F

and, $= 0.485 \times 10^{-9}$ ft. at 717°F (Critical Temp.),

the pressure being 14.7 lbs/sq. in., in both the cases.

This suggests that the nucleus bubble consists of one molecule. Then, the total interfacial energy of a lb. of single molecule bubbles (the limiting case) is given by

$$2u_3 = {}_2(u - Ts)_3 + {}_2(Ts)_3 = \frac{3\left(\sigma - T\frac{\delta\sigma}{\delta T}\right)v}{r} \quad \ldots \quad (0.26)$$

This suggests that the internal latent heat could be calculated from

$$u_{fg} = \frac{3\left(\sigma - T\frac{\delta\sigma}{\delta T}\right).v}{r} \quad \ldots \quad \ldots \quad (0.27)$$

Using interfacial energy from Landolt-Bornstein data at 212°F, u_{fg} = 920 B.Th.U/lb. Using the tabulated value 897.5 B.Th.U per lb., the corresponding value of r would be 0.512×10^{-9} ft.

Thus this theory leads to the conclusion that the nucleus bubble is of molecular dimension and that capillarity or surface tension may be a property of the molecule. This is contrary to the accepted theory of capillarity. This theory was developed to include the case of condensation of a supersaturated vapour and , there again, it led to the conclusion that the nucleus drop must be a single molecule. Larson cited many instances which lend support to his theory- especially the behaviour of catalysts. The ebullator may be looked upon as a catalyst whose role is to supply either a portion or all of the free energy required for the transformation to occur in the initial step. Most solid surfaces

are composite of various faces, edges, and corners of crystals or broken crystals. Thus it is natural to assume that a property such as contact angle would not be sensitive to the variations of adhesion free energy that may actually exist. This assumption, coupled with roughness or curvatures of molecular or unit crystal magnitude, may explain why bubbles form at particular spots on a solid. There is probably also reason to believe that a bubble will preferentially form in a cavity of molecular magnitude, provided the adhesion tension there is a minimum or negative.

****

PART II.

FOAMING IN BOILERS AND FOAM INHIBITION.

Substances in solution in water have a marked influence on the origin and developement of bubbles. Wetting agents lower the surface tension and aid in the formation of smaller bubbles with lesser superheat. However, excessive amounts of dissolved matter in boiler water cause the unpleasant phenomenon of foaming.[34,35,36,37] This necessitates "blowing down" - a wasteful thing - to keep down the concentration of both soluble and suspended matter which aid in foaming.

Foulk has advanced the idea (Ind. Eng. Chem., 25, 800, 1933) that the difference is caused by the increase in the stability of the bubbles which, like stable colloidal solutions, are prevented from coalescence, presumably by the action of electric double layers surrounding the individual bubbles. The origin of the postulated electric forces, however, cannot be the same as in colloidal solutions. It is known that the colloidal solution is stabilised by the Zeta-potential (or, Electrokinetic Potential) at the interface. However, in the course of a comprehensive investigation J. Perrin (1904) found that the magnitude and even the sign, of

the Zeta-potential could be altered by the presence of ions in the solution; hydrogen and hydroxyl ions are specially effecteve in many ways. (OH) ions make it more negative, in general. On the other hand, a boiler has to be blown down to keep down the concentration of electrolytes.

Adam[33] thinks the stabilisation may depend upon the building up of insoluble crystalline films such as carbonates, hydroxides, or sulphates precipitated around the bubble. This may not be the only reason because foaming has been observed with solutions.[34,35].

According to Cassel[34], the concentration of dissolved matter may cause stabilisation in two ways: First,by reducing vapour pressure because of the higher concentration which, in turn, causes a reduction of the rate of vaporisation. The growth of bubbles will be slowed down at an earlier stage. Hence superheating must increase resulting in more bubble formation on sufficiently active suspended particles. Second, the existence of a concentration gradient between the surface of the bubble and the interior of the solution implies the building up of an electrical potential difference whose magnitude depends on the transfer numbers and the activities of the electrolyte. This theory of Cassel's which explains the stabilisation of foam in boiling electrolyte solutions on the basis of the thermoelectric potential differences arising from the temp. gradient around

growing bubbles, has not been definitely confirmed. For instance, it should be expected that the tendency to foaming as measured by the height of the foam column obtained is proportional to the molar electrolyte concentration rather than to the weight of dissolved matter customarily used in water treatment calculations. Also, the correlation of foaming and the thermo-electrolytic potential differences characteristic of the solutions lacks definite confirmation. Cassel interprets the effect of foam inhibitors (e.g., castor oil) as a change in the rate of bubble creation caused by surface-conditioning of heating elements and suspended particles.

Jakoby and Bischmann[35] present a photographic study of the formation of steam bubbles at atmospheric pressure from smooth heated surfaces and surfaces coated with $CaCO_3$ scale. It is found that the nature of the surface has a marked effect on "nucleate" boiling, scaled surfaces giving a multitude of small bubbles with no tendency to collapse. Oleic acid (5p.p.m.) is found to induce film boiling at a Δt lower than before. In actual boiler operation, oil contamination of water may be continuous and aid substantially in overheating the boiler metal, although such contamination is rare now-a-days.

In studying the effect of a polyamide antifoam (a certain N-N'-disubstituted-dibasic acid amides of high molecular weight and polyacylated polyamides) on a boiling foaming solution, the action of the antifoam was shown to begin

at the heating surface (cf. fig. 34) causing not only collapse of the foam but also coalescence of the otherwise small bubbles before their detachment from the heating surface. Similar results were obtained at pressures of 70 p.p.i. and 250 p.p.i. The authors support Foulk's balanced layer theory. The pronounced surface activity of the antifoams is borne out by the destruction of the foam layer and the coalescence of the ascending steam bubbles. It becomes absorbed at each new steam-water interface.

Gunderson and Denman[37] attribute foaming to excessive concentration of electrolytes, alkalinity, colloids and organic surface-active substances etc., which cause increased wetting, a larger number of active nuclei, smaller and more stable bubbles and consequent decrease in the superheat of the water.

Photographic studies suggest that the alkylene polyamides bring about initial large bubble formation on the heating surface in an explosive manner and greatly reduce the number of bubbles; subsequent coalescence of the large bubbles is facilitated. Fewer bubble nuclei are active, and some nuclei seem to be preferentially activated, e.g., more hadrophobic in character, probably made so by the oriented adsorption of the polyamide molecules whereby the polar groups are adsorbed on the solid surface and the long hydrocarbon chains face the water. Nuclear boiling is maintained. The authors propose to prove this mechanism by introducing iso-

tope tracer atoms into the molecule and then photometrically checking up the establishment of these activated nuclei.

.....

PART III.

HEAT TRANSFER TO BOILING LIQUIDS.

Concentration of solutions by boiling off the excess liquid in suitable machines is a major industrial operation. An economical operation of these machines demands a high rate of heat transfer to the boiling liquid. Thus, heat transfer to boiling liquids forms an important problem. Boiling in these operations is invariably confined to the nucleate type which has already been shown to be more efficient than film boiling which is to be avoided not merely for economic reasons but also for reasons of safety in certain cases. This heat transfer is achieved from submerged surfaces which may be horizontal, vertical or inclined, and flat or tubular. The rate of heat transfer from the hot surface to the boiling liquid is primarily controlled by the thin film of liquid in contact with the hot surface.

As will be seen subsequently, several of the important factors which enter into the problem have similar effects at least qualitatively regardless of the shape, size, and orientation of the surface. Such factors are the temp. drop from the hot surface to the boiling liquid, nature of

the hot surface, the nature and physical properties of the liquid, pressure (or boiling point) and the dissolved substances, etc.

Factors Affecting the Coefficient of Heat Transfer.

There are several important factors which affect the rate of heat transfer to boiling liquids. These will be considered one by one in the light of recent researches.

1. Effect of Temp. drop, Δt :-

This is by far the most important factor. Its effect is best shown by the boiling curve already given which shows in a qualitative manner the effect of Δt on both, flux and the film coeff. The shape of the boiling curve is quite generally accepted.[1,2,3,6,7,8,10,] However, there is considerable difference of opinion as to its exact magnitude. Cryder and Finalborgo[40] found that their results could be correlated by

$$h = q (\Delta t)^n \quad \ldots \quad \ldots \quad \ldots \quad (0.28)$$

where the value of n lies between 2.4 and 2.5. They cite the relationship given by Jakob and Linke, which when suitably transformed takes the following form:-

$$h = C (\Delta t)^4 \quad \ldots \quad \ldots \quad \ldots \quad (0.29)$$

(where C is a constant).

Again, Insinger and Bliss[16] put

$$h \propto (Q / A\Theta)^{0.69} \quad \ldots \quad \ldots \quad \ldots \quad (0.31)$$

Now, $Q/A\Theta = h \cdot (\Delta t)$; hence the above relationship reduces to the form:-

$$h \propto (\Delta t)^{2.23} \quad \ldots \quad \ldots \quad \ldots \quad (0.32)$$

Lukomskiĭ (cited by Badger and Lindsay, Ind.Eng.Chem., 38, 30, 1946) presents a summary of boiling coefficients which, in general, can be expressed as :-

$$U = C \cdot \Delta t^{2.5} \quad \ldots \quad \ldots \quad \ldots \quad (0.33)$$

He reports that the ratio of heat flux to maximum heat flux (Q/Q_{max}) can be plotted against the ratio of the temp. difference to the critical temp. difference, ($\Delta t/\Delta t_{crit.}$). Bonilla and Perry[39], using a horizontal hot plate with pure liquids and their binary mixtures, found that in the high range of flux,

$$h \propto (\Delta t)^{2.23} \quad \ldots \quad \ldots \quad \ldots \quad (0.34)$$

2. Nature of the Surface -

For the same liquid the coefficient is found to vary from surface to surface. This may primarily be due to the free adhesion energy which may differ from system to system. It is well known that a wetted surface gives a better heat transfer[8,9,37], the bubbles being quickly sheared away by the liquid from the heating surface. The liquid being in contact with most of the heating surface, has a better chance of getting sufficient superheat. If the surface is non-wetted, flat bubbles form, occupy most of the surface and reduce the rate of heat trans-

fer.

Rhodes and Bridges[5] found that the presence on the metal surface of a thin film of material not readily wetted by the liquid tends to promote film boiling. In the nuclear region a very thin film of wax on heating surface has no effect on the film coefficient.

Cichelli and Bonilla[41], while boiling binary mixtures found that in one case fouled surface increased coeff. by 15°/o for the same temp. drop. Rhodes and Bridges[5] found contamination and chromium or chromium-plated surfaces to induce film boiling whereas Sauer[1] et al. found that, of Cr-plated Cu, Cu, Fe and Al, the first gave the highest flux. Bonilla and Perry[39] also found Cr surfaces to induce film boiling. They attributed this to a non-wettable thin film of oxide. For a Δt of 22°C ethanol gave a heat transfer coeff. of 4800 for polished Copper, 2200 for fresh gold plate, 1300 for fresh Cr-plate and 580 for aged Cr-plate.

Whereas Insinger and Bliss[16] found the coeffs. relatively unaffected by time in absence of contamination, in Sauer[1] et al's experiments copper was found to give large variations depending upon the length of time since cleaning, even though the deposit of foreign matter was barely perceptible. Overall coeff. from steam to water with an initially clean copper tube increased from 1150 to 5190 during the first 142 min. at a constant Δt. Bubble formation nuclei gradually increased in number and finally covered the

whole surface. However, the authors failed to duplicate results.

The overriding factor seems to be the fact that the surface must be thoroughly wetted so that heat may easily flow from the solid to the liquid and that, at the same time, there must be a sufficiently large number of points which can furnish nuclei for bubble formation.

While in two cases a rough surface was found to give a better heat transfer[1,3], in a third case no difference [3,p.303] was found when the results were based on the projected area. Sauer[1] et al found that, with water, for a temp. drop less than 125°F (steam to water), iron gave higher overall coeffs. than Cu or chromium-plated copper. On the other hand, Pridgeon and Badger[38] found the reverse to be true, and clearly some unrecognised factor played a dominant part.

3. Nature of the Liquid:-

For the same heating surface the film coeff. under similar conditions differs from liquid to liquid. Jakob[9] found that for water the coeff. was 2.5 times as grat as that for CCl_4. Cryder and Finalborgo[40]

boiled a number of liquids in the range of moderate flux. For a given Δt, the value of h (Film coeff.,B.Th.U./hr/sq.ft/^{o}F) for methanol is 12% of that of water, but for a given flux the value is 55% of that for water. Variation from liquid to liquid is always to be expected although no rule can be given for predicting values.

Bonilla and Perry[39] found that the coefficients for binary liquids lie between those for the individual components. Work on im-miscible liquid mixtures by Bonilla and Eisenberg[42] showed that, for the same flux, (B.Th.U./hr./sq.ft.), a higher Δt was necessary than for the pure liquids. Also, considerable superheating is to be expected in the boiling of shallow liquid layers of the order of 2.5 inches, in contrast with the boiling of partly soluble liquids.

Sauer et al[1] found that the maximum flux for the non-polar group ethyl acetate, C_6H_6, CCl_4, and Heptane was the least, intermediate for $CH_3.OH$ and $C_2H_5.OH$, and the highest for water.

4. Pressure (or, Boiling Temp.):-

It is generally found that as the pressure is lowered the coeff. is also reduced[3,4,5,16,39,40]. but the critical temp. difference remains sensibly constant[8]. According to Cryder and Finalborgo[40], for eight liquids experimented upon, for pressures above and below atmospheric,

$$\log \frac{h_a}{h} = a_1 (t_a - t) , \quad \ldots \quad \ldots \quad \ldots (0.35)$$

where h_a and t_a are the coeff. and boiling point at atmospheric pressure. "a_1" differs from liquid to liquid and for water it ranged from 0.012 to 0.017. This simple relation could not correlate the data of Braunlich or those of Kaulakis and Sherman.[3,p.309] When water was boiled at different elevated pressures, Farber and Scorah[7], working with hot wires, found that the same heated metal gave different boiling curves, though the general form remained the same.

The fall in h with decrease in pressure may be attributed to the increase in the specific volume of the vapour, with resulting increase in blanketing action. The increase in the viscosity of the liquid which occurs when the pressure and, therefore, the temperature is reduced, may also be a factor in determining the change in the film conductance[5]. Yet another factor figuring here may be surface tension which increases with temperature fall.

Bogart and Johnson (Ref.3, P.310), working with a submerged horizontal Ni tube at high pressures, found that with benzene, at a given Δt, an increase in temp. and pressure gave an increase in h all the way from atmospheric to critical pressure, in spite of the fact that a carbonaceous deposit formed on the tube due to thermal decomposition under excessive Δt.[3(p.310)]

However, there is no agreement as to the exact effect of pressure on the coefficient[3,309]. Also Akin & McAdams[4] state that the percentage reduction in h with decrease in B.P. was not so large in their experiments as reported by Cryder & Finalborgo[40].

Bonilla and Perry[39] working with binary mixtures of miscible liquids found

$$h = b.P^{0.25}, \quad \text{where } b = \text{constant.}$$

Also as P (in atmospheres) rises, the ratio, $\frac{(q_{max})_P}{(q_{max})_a}$, rises first rapidly and then more slowly, P referring to the pressure other than atmospheric and "a" to the atmospheric pressure. These relationships were also found to apply to the data of Akin and McAdams.

5. Effect of Addition Agents:-

Wetting agents increase the rate of heat transfer by reducing the surface tension and aiding in the formation of bubbles. Here again there is disagreement with regard to its exact effect. According to Jakob[9],

$$h = \varphi(\sigma)^{-0.5} \quad \ldots \quad \ldots \quad \ldots \quad (0.36)$$

based on observations with NEKAL BX which reduced surface tension by 45% and increased h by 23 %. Insinger and Bliss[16] put

$$h = \varphi(\sigma)^{-0.62} \quad \ldots \quad \ldots \quad \ldots \quad (0.37)$$

On the effect of other addition agents, the results of Rhodes and Bridges[5] are very interesting (see also Ref.3, pp. 303, 304). In general it could be said that anything that improves the wetting of the surface by the liquid, improves the film coeff., and anything that reduces the wetting of the surface lowers the film coeff., too.

6. Effect of Viscosity:-

Whereas in the simple heating of fluids viscosity plays an important role (consider for example Dittus - Boelter Equation) it is somewhat surprising that with boiling liquids its effect according to Insinger and Bliss[16] is negligible. Rhodes and Bridges[5] consider viscosity to be of importance but did not investigate its effects. However, work on LTV, Short-Tube, Vertical and Forced Circulation evaporators has shown that viscosity does play an important part.

7. Effect of Agitation:-

McAdams (Ref.3, p.306) shows how Austin's results in the range of nucleate boiling with liquid stirred, indicate no change in h with increasing Δt; and h is higher than for an unstirred liquid for the same value of Δt.

8. Effect of Tube Dia. does not seem to be of much consequence (see Ref. 3, p.314).

9. Correlation :-

There have hardly been any general correlations in this field. Insinger and Bliss[16] gave the following correlation which fitted their own data and those of others, among them Linden and Montillon[53], and Akin and McAdams[4]. A closer examination of this correlation,

$$\log Y' = -2.751 + 0.451 \log X' - 0.076(\log X')^2$$

where

$$Y' = \frac{\left(\frac{h}{c\rho_L r^{0.5}}\right)}{\left(\frac{r^{0.5}\mu}{\sigma}\right)^{0.62}\left(\frac{\kappa}{c\mu}\right)^{0.49}\left(\frac{\rho_L}{\rho_v}\right)^{0.49}}$$

and

$$X' = \left(\frac{Q}{A\theta\rho_L r^{1.5}}\right),$$

shows, however, that it amounts to correlating h vs. Q, i.e., h vs. $h \cdot \Delta t$, a method which has been adversely criticised.

xx.x.x.x.x.xx

HEAT TRANSFER TO BOILING LIQUIDS FROM SPECIAL SURFACES

In view of the importance placed upon practical design in industrial heat transfer, it is surprising that the above discussions, which were confined to a variety of physical arrangement of the heating surface, generally lead to the conclusion that the latter factor is of little consequence so long as other conditions are the same. For example, Jakob's[9] results show that a horizontal plate gives as good results as a vertical surface both for water and CCl_4, boiling at atmospheric pressure. Sauer[1] et al, using both horizontal and vertical copper surfaces, found similar results with the same liquid. Akin & McAdams[4] worked with a model evaporator containing 60 nearly horizontal, chrome-plated, ½ in. Copper tubes to boil water at atmospheric pressure with overall temp. differences ranging from 20° - 100° F. The bundle gave the same results as the single tube apparatus which consisted of a horizontal 3/4 in. Ni-plated Cu-Tube. Other observers (cited by Ref. 3, p.313) found similar agreement.

One of the most important applications of heat transfer to boiling liquids is evaporation. The conditions under which it is carried out in practice are widely varied. The liquid to be evaporated may have a very

low or a very high viscosity. It may deposit scale on the heating surface; it may precipitate crystals; it may tend to foam; or, it may have a very high boiling point. This wide variety of problems has led to considerable variation in the types of mechanical construction used. In the past practical considerations and the customs of the various industries have influenced the design of evaporators to a considerable extent. Within the past two decades, however, greater and greater effort has been made to investigate the effect of various factors which affect and control heat transfer in evaporators so that a design of the latter could be reduced to a logical basis.

Since in industry most of the evaporator types use vertical tubes, most of the researches in recent years have been carried out using vertical tubes which are heated from outside and into which the liquid is fed from the bottom. Usually single tubes have been used for experimental purposes.

Vertical-Tube Evaporators.

It is porbably the most important type now in existence in industry. These have been favoured because the boiling inside the tubes induces a large velocity giving high rates of heat transfer. Sometimes this high velocity is achieved by pumping the feed at a high rate.

Thus, these machines may be either of the "natural-circulation" type or of the "forced-circulation" type. In either case, the unevaporated liquid recirculates through the tubes, entering at the saturation temp. corresponding to the pressure in the vapour-liquid separator. As the pressure at the bottom of the tube is higher than at the top, the liquid progresses up gaining in temp. and probably without boiling. A stage comes when boiling commences after which the temp. of the liquid falls progressively. Fig. 0.6 shows the curve for the feed temperature, as the liquid ascends the tube. The part of the tube needed for heating the feed to the boiling point (i.e., the temp. of the liquid at the point where boiling commences) is called the non-boiling or the heating section and the remainder, the boiling section of the tube. Thus, the maximum temp. of the feed is at the level where the non-boiling and the boiling sections meet. Kirschbaum et al (cited by Ref.44) first advocated the division of the tube into non-boiling and boiling sections. This suggestion was supported by Boarts and put to use by Badger and his associates (44,49,50)

The Long-Tube, Vertical, Natural-Circulation, Evaporator:-

The tube in these machines may be upto 22 ft.long. They have received increasing importance in recent years

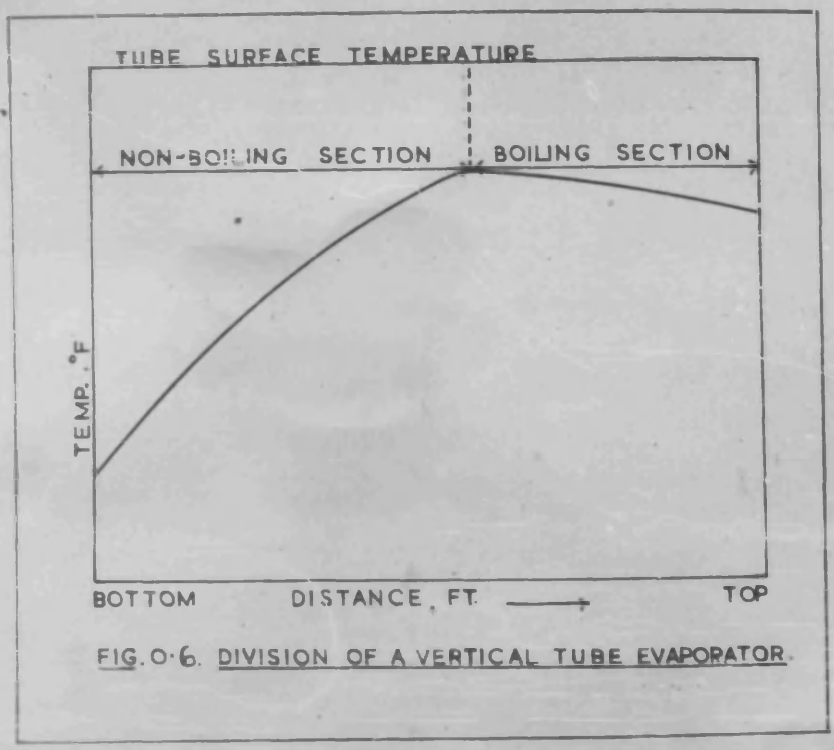


FIG. 0·6. DIVISION OF A VERTICAL TUBE EVAPORATOR.

because of their ability to handle heat-sensitive, foaming or viscous solutions which cannot be dealt with in the ordinary evaporators. The LTV evaporator is free from scaling trouble. The feed velocity is kept low so that considerable vaporisation occurs inducing high velocities in the tube without the need of pumping energy. The result is a high coeff. of heat transfer. Most of the work on this type of machine has been done by Badger and his associates.

The mechanism of boiling in vertical-tube, natural-circulation, evaporators has been given by Brooks and Badger.[44] Barbet [Bull.Assoc.Chem.Sucr., 32, 111,(1914), cited by Ref.44] described in great detail the appearance of the liquid when boiling occurs. He states that with low inlet velocities of the order of 0.3 ft/sec., bubbles form, which coalesce, pushing slugs of liquid ahead of them. Due to attrition at the walls of the tube these slugs become thinner and then break, allowing the vapour to pass through. If vaporisation is sufficient, the liquid on the walls of the tube will move upward. Mention was made that annular rings of liquid appeared on the wall of the tube, above the point where the slugs broke.

Brooks and Badger repeated these experiments using a glass tube, 3/8 in. o.d., in a glass steam jacket. Barbet's results were verified, i.e., progressing up the tube the following kinds of action were encountered:-

(1) A very short length in which the vapour and the liquid were more or less uniformly distributed.

(2) A section of slug action in which the transverse distribution is uniform, but the longitudinal is not, i.e., there are alternate slugs of liquid and vapour.

(3) A section in which "film" action occurs, or the longitudinal distribution is uniform, but the transverse is not, i.e., there is a core of vapour with the liquid in a film of varying thickness on the walls of the tube. The annular rings mentioned by Barbet also appeared in this section.

Two sight glasses were then set at the level of the upper tube sheet of the metal tube evaporator. These permitted observation of the outlet of the tube.

With boiling lengths of 1 ft. or less, froth appeared corresponding to (1) above. With small temp. differences the liquid came out in slugs, travelling at high velocity, with quiet intervals between the slugs. This corresponds to the second type of action.

As the temp. difference and the boiling length increased, two types of spray, coarse and fine, began to appear. The coarse spray seemed to be travelling at a much slower velocity than the fine spray. The fine spray seemed to be in the centre of the tube, whereas the coarse was on

the outside. The coarse spray appeared, in most cases, to be blown outward, while the fine spray travelled up to the deflector in a st. line.

If there were a film of liquid on the walls of the tube, it would tend to be blown outward, in the form of spray, as soon as the retaining walls of the tube were removed. On the other hand, if there were drops of liquid in the vapour stream, they would tend to travel in a straight line for a time, due to their momentum, even though the line of motion of the vapour changed. Hence, it appears that action according to (3) above does actually take place with the addition of a phenomenon not yet explained.

Kirschbaum and his associates [Forschungsheft, 375, Nov.-Dec., 1935, Page 1] showed that in the boiling section the temp. distribution across the tube was practically uniform for almost the entire cross-section, but it climbed very rapidly at the walls. Since the static pressure at the walls would be the same as that at the centre of the tube, boiling should occur at the wall. The formation of a bubble of vapour, and its subsequent release into the main vapour stream, by bursting, undoubtedly would tend to produce drops. Some of these would be thrown over to the other side of the tube, i.e., back into the liquid film. The remainder might stay in the vapour stream to form the fine spray observed.

Hence, it would appear that in progressing upward from the boiling level, a section of froth is found, then slug action, followed by film action, superimposed upon which there may be more or less spray. The temp. difference and the boiling length, and possibly the amount of liquid present, determine the action occurring at the outlet of the tube. The relation between the operating variables and the types of action is not yet known. Stroebe et al[45] confirmed the above observations and found that for high Δt, the coarse spray diminished or entirely disappeared, suggesting that the film became thinner towards the top, disappearing in some cases, leaving the top of the tube dry. Brooks and Badger[44] measured the temp. distribution in an LTV evaporator (single Cu Tube, 1.76 in.x20ft.) True overall Coeffs., U_B, for the boiling section were determined for distilled water boiling at temps. ranging from 150 to 200°F. The data show that U_B increased with increase in the fraction of the feed evaporated. Stroebe, Baker and Badger[45] used the same apparatus and boiling points for water, sugar solutions & "Duponol" solution, but injected enough live steam to obtain a boiling throughout the tube. The values of h_m ranged from 1160 to 2640 which are considerably lower than those obtained by Boarts with forced circulation.

Stroebe[45] et al gave the following correlation for their results:-

$$h_l = \frac{7.8 \times 10^6 \cdot v^{0.1}}{\left(\frac{c_p \mu}{k}\right)^{0.3} \sigma^2 (\Delta t_l)^{0.13}}$$

where, h_l = Boiling Liquid Film Coeff., B.Th.U/hr/sq.ft/^oF,

v = Sp. Volume of vapour, $ft^3/lb.$,

σ = Surface tension, and

Δt_l = Liquid film temp. difference, ^oF.

The effect of surface tension on h_l was high. For example in a run with water, entering at a velocity of 0.2ft/sec. and a temperature of 155^oF in vapour separator, h_l was 1500, but on adding a small concentration of a wetting agent, Duponol, h_l increased to 3100 and U_B increased from 540 to 710 units. It is surprising that Δt_l should have caused any reduction in h_l, however small. The authors explained this by assuming that, with low feed rates, only a part of the tube was wetted by the liquid, leaving the remainder dry.

Cessna, Lientz and Badger[49] reported overall coeffs. for a vertical copper tube (1.25 in. x 18.5 ft.) and calculated true overall coeffs., U_{NB} and U_B, for the non-boiling and the boiling sections for water and solutions containing from 30 to 50 per cent sucrose. The values of U_{NB} were correlated by the natural-convection type formula :-

$$U_{NB} = 0.06 \left(c_p \Delta t_m \rho^2 / \mu\right)^{0.7}_{NB}.$$

Cessna and Badger[50] used a vertical copper tube (0.65 in. x 18.5 ft.) and repeating the above work (Ref.49), gave a complex equation for correlating the maximum temperature of the liquid in the tube and reported overall coeffs., U_{NB} and U_B.

The Short-Tube, Vertical, Evaporator.

It is essentially of the natural-circulation type and is quite generally used. The tubes may range from 1 in. - 4 ins. in dia., from 30 ins. to 6 ft. long.

Badger and Shepard[51] used a basket type evaporator containing 24 iron-tubes (2in. x 2ft.) and found that the overall coeff.,U, increased with increase in the overall temp. drop, Δt_o, and with increase in the temperature of boiling.

Webre &Robinson("Evaporation" - Chemical Catalog Co., 1926) presented a theoretical analysis of the rate of liquid circulation in evaporators. This analysis was neither accurate nor applicable over a variety of conditions. Linden and Montillon[53] presented a very accurate study of circulation using a single 4ft. long inclined tube evaporator.

Foust, Baker and Badger[43] studied evaporation of water in a basket type evaporator (steel tubes, 2,5 in.o.d.

x 4 ft.) under reduced pressure and measured circulation by a pitot tube. The overall coeff. increased with lowered level of the liquor, with increased overall Δt, and with increased boiling point. The velocity ranged from 1 to 4 ft/sec. and for each value of overall temp. drop went through a maximum with respect to liquor level. Apparent values of U ranged from 76 to 309, and true values from 78 to 340.

THE FORCED-CIRCULATION EVAPORATOR.

These machines are shorter (usually 3/4 " I.D. x 8 ft. long) than the LTV evaporators and a high velocity inside the tube is obtained by forced circulation. Since the rate of feed is usually very high, a high rate of heat transfer is obtained, but, as the tubes are rather short, little or no boiling occurs in the tubes. As the feed is discharged into the vapour space it undergoes flashing releasing the vapour. This evaporator is especially suited for foamy liquids, for viscous liquids, and for those which tend to deposit scale or crystals on the heating surfaces.

Badger, Monrad and Diamond[48] reported film and overall coeffs. for concentrated caustic solutions for a vertical, Nickel tube heated by condensing vapours of

diphenyl. Overall coeffs. for gelatine and molasses solutions are given by Coates and Badger.[47]

Logan, Fragen and Badger[52] using a semi-commercial evaporator (Cu tubes, 8ft. x 0.75 in. i.d.) for sucrose solutions found that coeffs. calculated by the Dittus-Boelter equation were slightly higher than their results which could be correlated within 10 percent by

$$\frac{hD}{k} = 0.0205 \left(\frac{Dv\rho}{\mu}\right)^{0.8} \left(\frac{c\mu}{k}\right)^{0.4} \quad \ldots \quad \ldots$$

They thought that this might be due to the insulating effect of the vapours in contact with the tube wall in the boiling section tending to lower the coeff.

Boarts et al[46], using a single copper tube (12 ft. x 0.76 in. i.d.) evaporated distilled water at apparent boiling points of 140° to 212°F and reported film coeffs., temp. measurements having been made with wall thermocouples and a travelling thermocouple. With no boiling and Re above 65,000, h_m, based on the length mean temp. drop, was 1.26 times the value predicted by the D. and B. equation. With appreciable boiling (evaporation up to 6.5 p.c.) the results were higher by 140 percent.

McAdams[3] (p.322) shows how Boarts's results

follow those of Oliver[55] who worked with a short, vertical, nickel tube (0.495 in. x 1.72 ft.), for Re greater than 65,000; in the case of both investigators, both flux and film coeff. increase with Δt.

Mechanism of Heat Transfer in a Forced-Circulation Evaporator:

Based on his observations Boarts[46] gave an explanation of the mechanism of heat transfer in a forced-circulation evaporator.

The liquid enters the tubes of the evaporator at substantially the temp. in the vapour space, and gets superheated above this temp. in going up the tube. The liquid is kept from vaporising by the hydrostatic and the friction heads above it. In this region the Dittus and Boelter equation holds. This equation is based on the Nusselt theory of heat transfer to liquids in pipes based on conduction through the viscous film and convection through the bulk of the liquid. For condensing of steam on the outside of pipes it is now well known that drop-wise condensation can produce coeffs. 4 to 8 times those for viscous film condensation. If the production of a drop of water from steam can be so much more effective than transferring heat through a viscous film of condensate on the tube, then it is possible that steam bubble

formation on the inside of the tube would likewise be a better heat transmission agency than a viscous film. The minute drop so formed is removed immediately and convection into the cooler bulk of water condenses it. Such mechanism would account for the uniformly higher coeffs. obtained than the D. and B. equation predicts.

As the superheated liquid goes higher, both Re and Pr. increase and so the heat transfer through the viscous film increases due to scouring effects. A stage is reached when stable bubble evolution occurs, since the hydrostatic and friction heads can no longer overcome it. This induces a large velocity which reduces the thermal resistance of the liquid film over the boiling section. The liquid film coeffs. for the boiling section were approximately twice those for the non-boiling section.

The temp. difference drops smoothly with increasing heat input indicating a progressive vaporisation in the tube, showing that tube-wall and liquid temperatures are inter-dependent.

Near the top of the tube all temperature drops over the liquid film approach a constant value for all velocities, requiring the tube-wall temp. to rise; the meaning of this is somewhat obscure.

If this hypothesis be true, the determination

of boiling coeffs. becomes a matter of the degree of the relative predominance of the three actions. Possibly the best correlation of this mixed mechanism would be on the basis of the per cent liquid evaporated.

...oooOooo...

C O N C L U S I O N

The above review reveals the volume of work that has been done in an attempt to develop a satisfactory theory of boiling and of heat transfer to boiling liquids. The available data do not lend themselves to theoretical treatment or even to the formulation of empirical generalisations. Every worker has attempted to correlate data but these correlations are only empirical and apply to the piece of apparatus used and the range covered with regard to important variables. The factors which enter the problem are many. Not all of them are understood. There is no agreement yet on the quantitative effects of those that are known. Sometimes there is difference of opinion even with regard to the qualitative effect of others.

Each solid-liquid pair has to be trated on its own merits as in the science of surface chemistry. In empirical correlations of the coefficient to various physical properties, the properties of the liquid alone have been introduced to the neglect of those of the solid. It may well be that a more important property than the surface tension of the liquid is adhesion of the liquid to the solid surface, a quantity which has the merit of taking into account the nature of the surface.

C H A P T E R. I.

THE GLASS-TUBE, VERTICAL, NATURAL-CIRCULATION EVAPORATOR.

CHAPTER I.

The Pyrex Glass-Tube, Vertical, Natural-Circulation, Evaporator .

This chapter deals with investigations which have been made with a Pyrex glass-tube, not merely for observations on the nature of boiling of the various liquids but also for finding overall coefficients, both for the entire tube and for the Boiling-Section, for water, 0.1 % Perminal W.A. (an I.C.I. wetting agent) Aqueous Solution, 95.6 % Ethyl Alcohol and Toluene, at temperatures far below their boiling points under atmospheric pressure. One special feature of the experimental technique is the use of hot water, at a high velocity, for heating the tube, and the other is the use of a Differential Thermocouple System for measuring the temperature drop from hot water to feed liquid, all along the length of the tube.

There is, as far as is known, no record of any such evaporator having been used for the study of heat transfer to boiling liquids. The only use of glass-tubes, in such studies, seems to have been confined to observations on the nature of boiling (see, for example, Brooks and Badger[44]).

The Apparatus.

The complete assembly is shown in Fig. 1.2, and the glass-tube, along with its jacket and the feeder, is shown in Fig. 1.1.

The evaporator unit consisted of a Pyrex glass-tube (7/8 in. O.D. x 3/4 in. I.D. x 9 ft. long) with a Quick-fit ground-glass joint at each end. This tube was heated for 7 ft. 10½ in. of its length by hot water circulated at the rate of about 20 galls/min. through the Pyrex glass-tube jacket ($1\frac{9}{16}$ in. O.D. x 8 ft. 1 in. long). The evaporator tube and its jacket were held together by means of rubber-bungs. The jacket had two side-tubes, about 7/8 in. O.D. by 3 in. long, fused near the bottom and the top, to serve as "inlet" and "outlet" for hot water. A straight piece of glass-tube (7/8 in. O.D. x 1 ft. long) with a ½ in. i.d. side-tube fused at about 3 in. from the top, had a Quick-fit joint at the lower end, and fitted the top of the evaporator tube. Through a rubber-bung fitted to the upper end of this top-piece, passed a $\frac{3}{32}$ in. O.D. glass-tube thermocouple pocket extending to the level of the bottom of the heating jacket. This thermocouple pocket was centred by means of 3-legged "spiders" fixed at 3 ft. intervals.

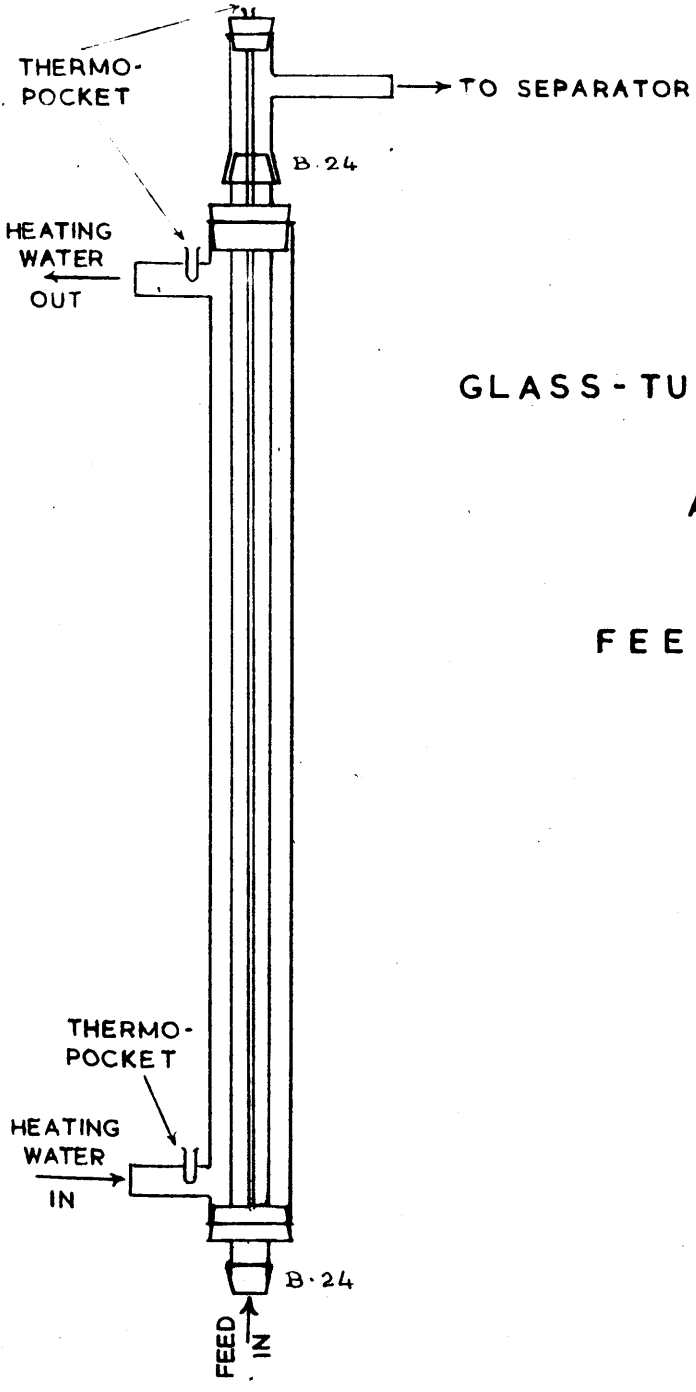


FIG. 1·1

GLASS-TUBE EVAPORATOR

AND

FEEDER.

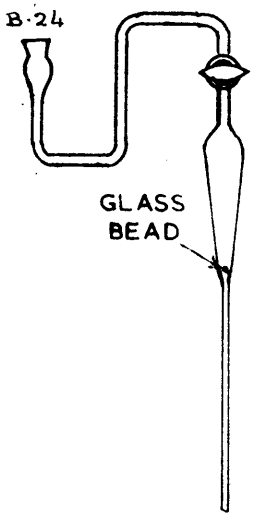
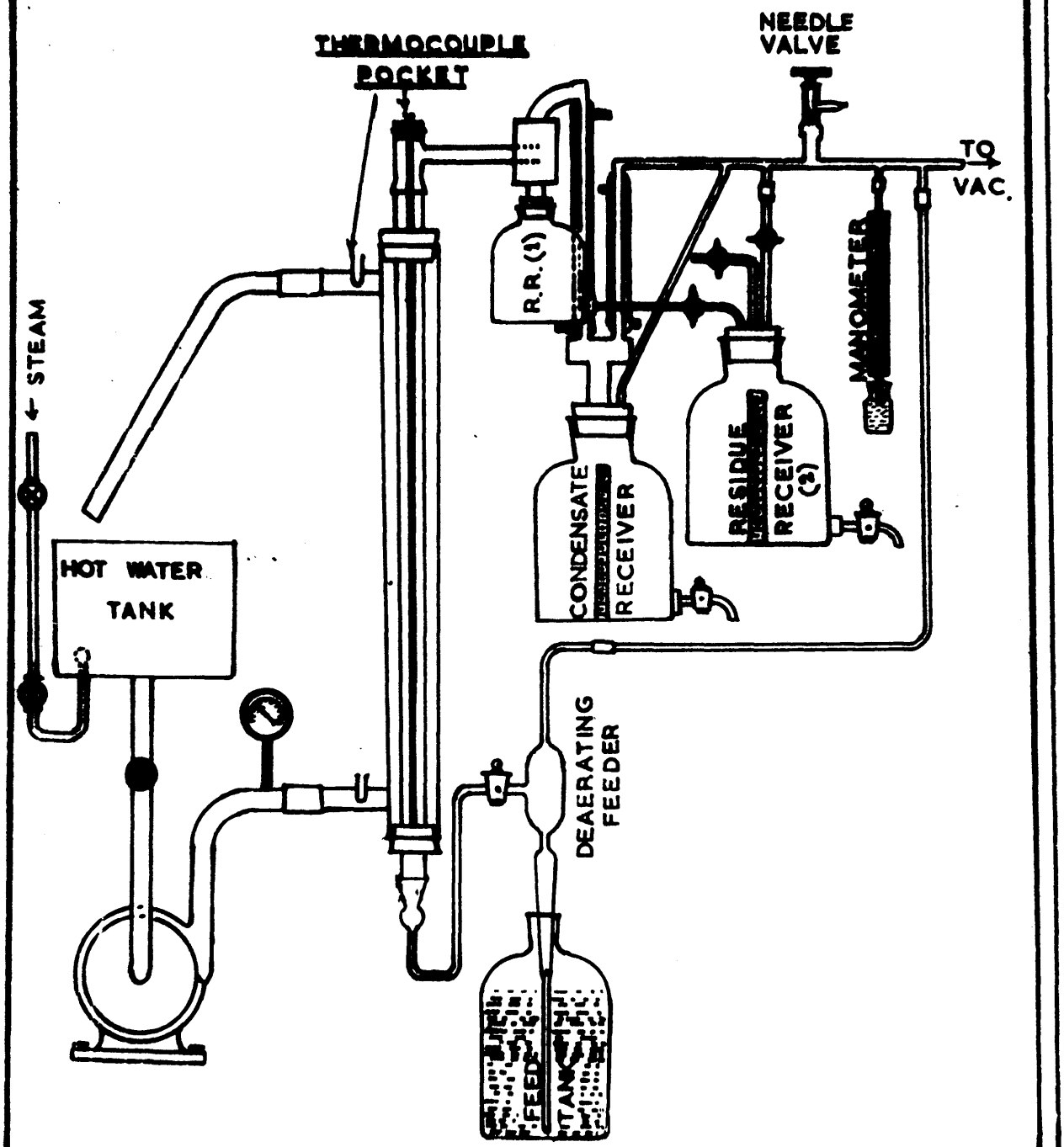


FIG. 1.2. GLASS-TUBE EVAPORATOR.



Each of the side-tubes of the heating jacket had a ½ in. O.D. glass-tube pocket fused into it for holding a thermometer and a thermocouple.

The lower side-tube of the jacket was connected by means of a reinforced rubber-tubing to a 1-inch Copper hose, communicating with a 200-gallon capacity hot-water tank through a centrifugal pump. A metal tube similarly connected to the upper side-tube served to return the hot-water back to the tank.

The side-arm of the top-piece of the evaporator tube was connected by means of rubber tube to a Separator. This was a Stainless Steel cylinder, 14 in. long by 3¼ in. O.D. with a tangential inlet. An S.S. pipe (5½ in. long x 1 1/16 in. O.D.) was welded to the base of the Separator and drained off the liquid residues to receivers. A curved 1⅕ in. O.D., S.S. pipe, welded to the top of the separator and to the inlet of the condensing system, served to remove the vapour.

The condenser was U-shaped with two upright limbs jacketed with water. It was made of Stainless Steel pipe, 1¼ in. O.D., and the limbs were 6 ft. and 3 ft. long, respectively. The condensed vapour drained into the condensate receiver, a graduated, 15-litre, Pyrex Aspirator.

The liquid residues flowed into two aspirators,

2½ litres and 5½ litres, respectively, one above the other and joined by a glass-tube having a stop-cock. The 5½ litre vessel was graduated in 50 c.c. divisions and had a lead to vacuum and another to the atmosphere, each through a stop-cock. This arrangement allowed the lower, graduated vessel to be emptied, re-evacuated and then connected to the upper receiver without disturbing the experiment. A ½ in. O.D. tube welded to the top of the short condenser tube provided a vacuum lead. The vacuum was provided by a vacuum pump connected to the apparatus through a trap and a drying tower. It was maintained at the desired level by means of a hand-operated needle valve.

The feed entered the tube through a measuring device, consisting of a glass-bead in a tapering glass-tube. Rates were controlled by a stop-cock and measured ultimately by weighing.

The purpose of using hot water at a high velocity for heating the tube was to have the film coeff. of the heating agent to be maintained at a high constant value.

The Deaerating Feeder -

The feeder mentioned earlier and shown in Fig. 1.1 was used only for some preliminary investigations. It was found that much air leaked into the

system through its stop-cock. Consequently, in all the tests reported here, the Deaerating Feeder shown in Fig. 1.11 was used. It was connected directly to the vacuum line at a point higher than the top of the evaporator. This allowed most of the air to be got rid of, before the feed entered the evaporator tube.

Temperature Measurement:-

The temperature of heating water at inlet and outlet was read directly by thermometers in the appropriate thermopockets. The temperature of the feed, before entering the tube, was similarly read from a thermometer in the feed container.

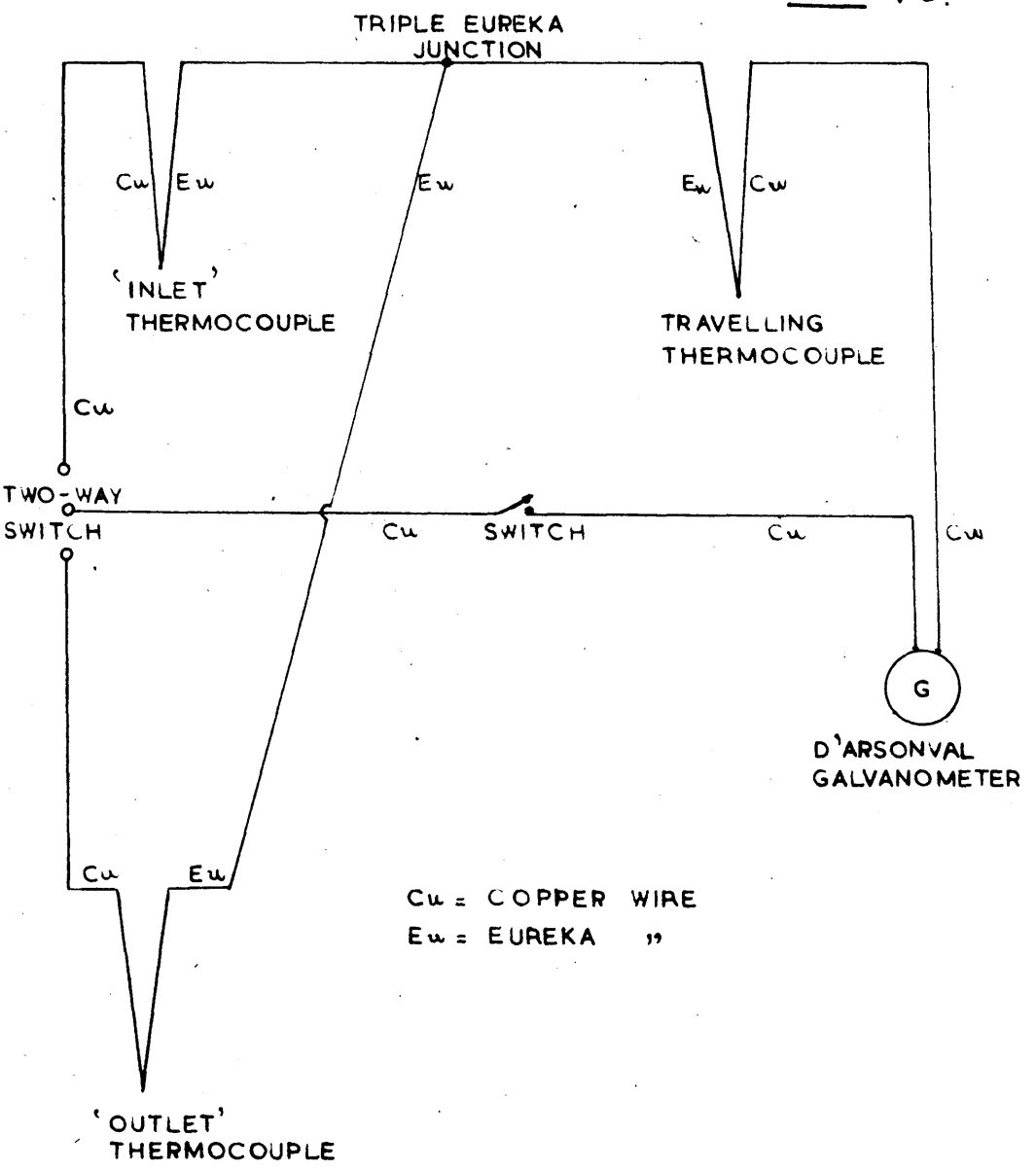
The actual temperature drop from the heating water to the liquid inside the tube was measured by means of a differential thermocouple system.

The Differential Thermocouple System:-

This is shown diagramatically in Fig. 1.3. A D'Arsonval Type Galvanometer was used to measure differential E.M.F.

The thermocouples were made from Copper and Eureka wires, each 24 S.W.G. and japanned for insulation. A thermocouple was fixed at the "inlet" and at the "outlet" of the heating jacket. A third couple, known as the Travelling Thermocouple, was made to record the temperature of the feed liquid inside the evaporator tube, and it moved inside a glass-tube pocket. The two wires of

FIG. 1·3.



DIFFERENTIAL THERMOCOUPLE SYSTEM

the travelling thermocouple were twisted together to impart them strength and thus prevent them from kinking when the thermocouple was moved up and down the thermopocket.

The free ends of the three Eureka wires were soldered together to form a Triple Junction. From Fig. 1.3 it is evident that, by means of the two-way key, either the "inlet" or the "outlet" thermocouple could be matched against the travelling thermocouple.

The travelling thermocouple was marked with white paint at suitable intervals (so that its position could be checked) and fixed over a pulley so as to pass evenly up and down the tube.

Calibration of the Thermocouples:-

The "inlet" and "outlet" thermocouples were inserted into their respective thermopockets of the heating jacket side-tubes, together with a thermometer. Hot water at either 50°C or 80°C , the two operating temperatures, was circulated through the jacket. The"travelling thermocouple" was inserted into a glass-tube sheath, 1ft. long(x $\frac{3}{32}$ in. O.D., kept in a bath of water whose temperature could be maintained at any desired level.

Deflections of the galvanometer spot corresponding to any given temperature difference were recorded for

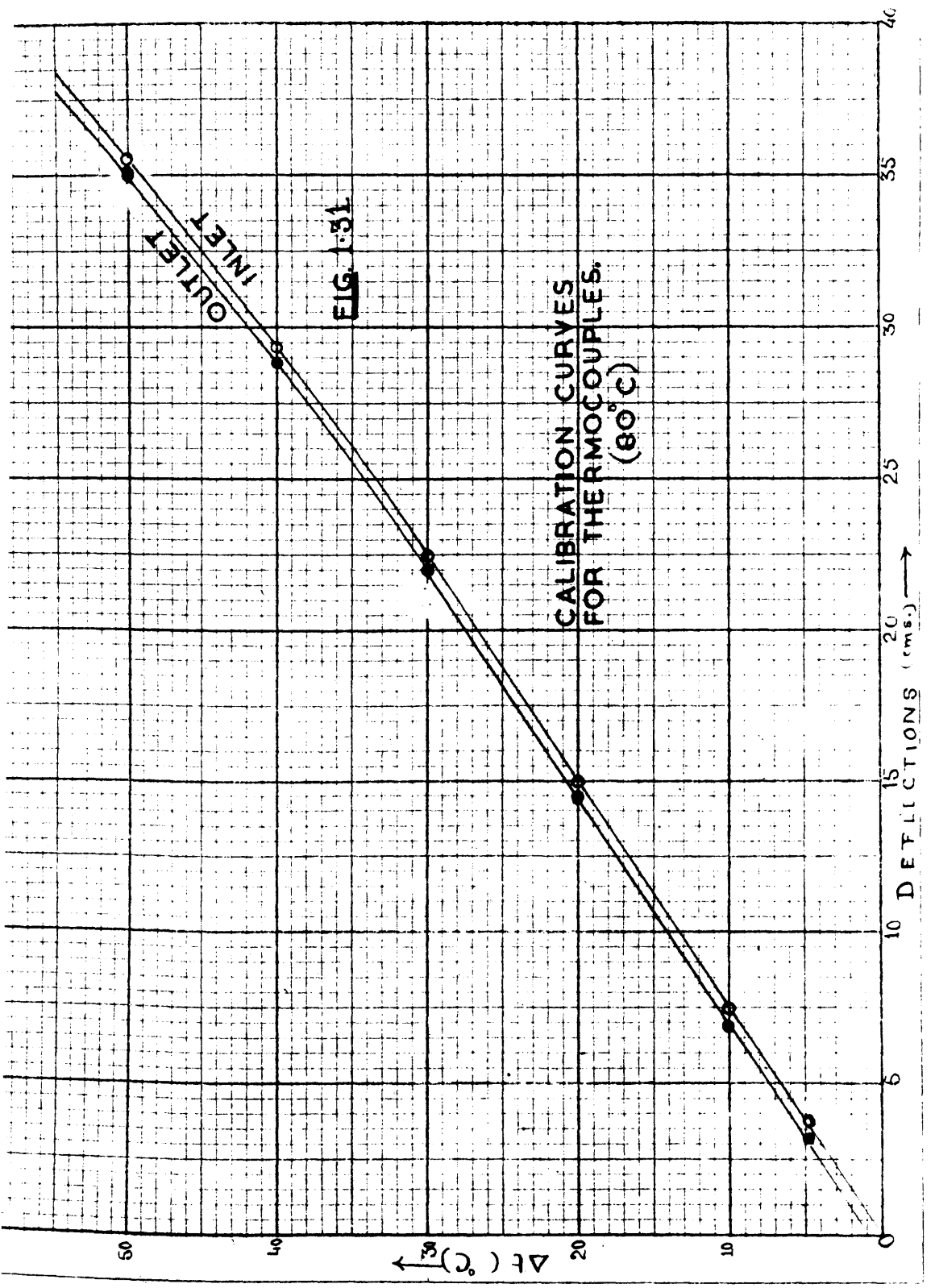
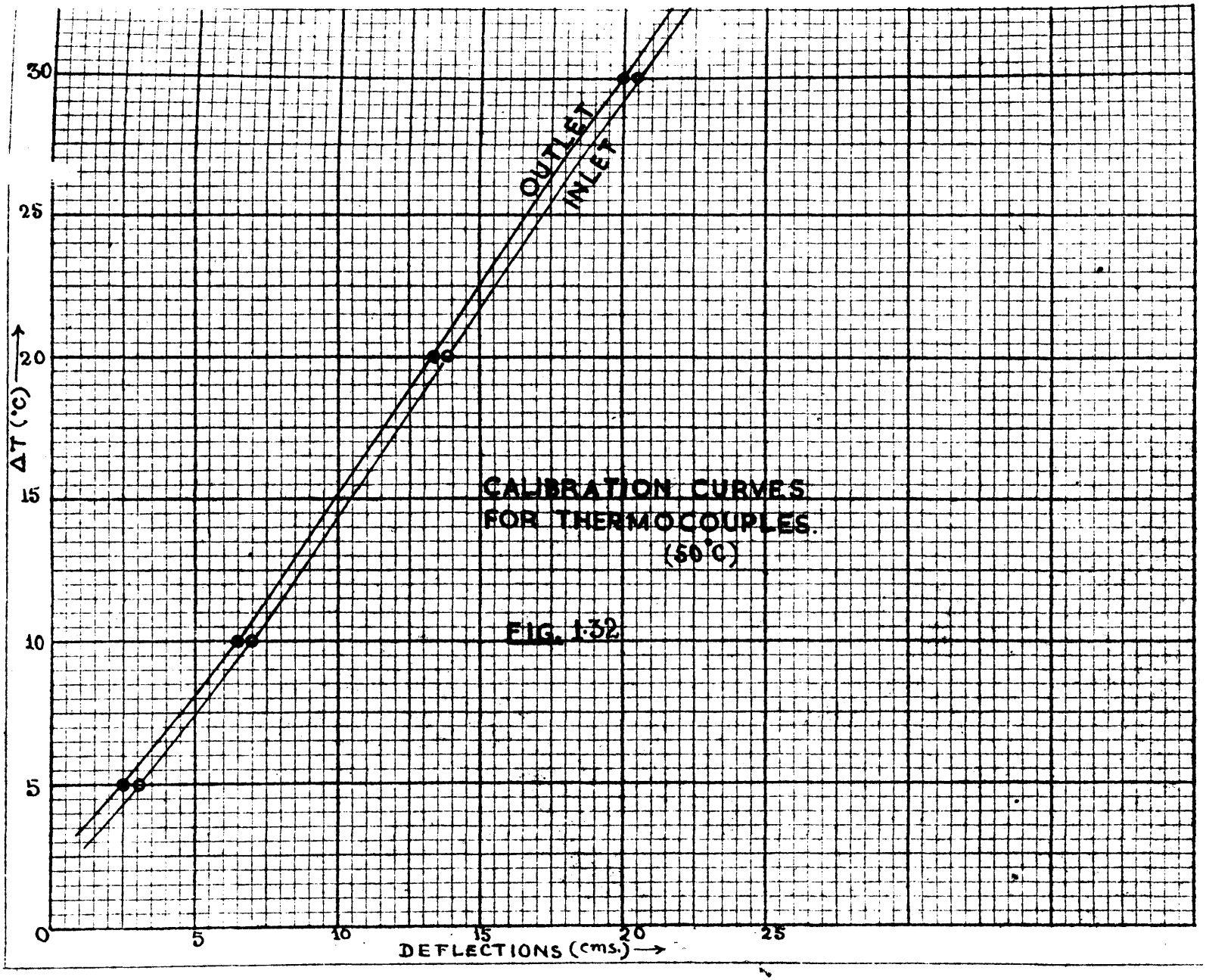

CALIBRATION CURVES
FOR THERMOCOUPLES.
(80°C)
OUTLET
INLET
DEFLECTIONS (mm.) →
Δt (°C) →
0
5
10
15
20
25
30
35
40
10
20
30
40
50

FIG. 1.31



CALIBRATION CURVES FOR THERMOCOUPLES. (50°C)

FIG. 1.32

both the "inlet" and the "outlet" thermocouple by including each in the circuit by turns. Then for each of the "inlet" and the "outlet" thermocouple, a graph of Δt vs. Deflection was plotted (Figs. 1.31 & 1.32). A deflection of X divisions for Y°C was obtained so that temperature difference could be recorded to ± o.05°C.

Experiment Procedure:-

Hot water, from the hot-water tank, was circulated through the evaporator jacket. The hot water tank was hand-controlled at a steady temperature by direct steam. This was either 80°C or 50°C according to the experiment being carried out. For example, in experiments on water and on toluene it was always maintained at 80°C and in experiments on ethyl alcohol it was usually at 50°C.

The stop-cock of the feeder was closed, cooling water to the condensers was turned on, the whole system closed to the atmosphere and opened to the vacuum line, and the vacuum pump started. By manipulating the hand-valve, the vacuum was brought to the desired level. The stop-cock of the feeder was now adjusted to give the desired rate of flow.

The "residue" and the "condensate" collected in their respective receivers. The apparatus was allowed

to run for about 15 minutes for steady conditions to be attained.

The test was then started; the level of the liquid in the "condensate" receiver was noted, while the stop-cock between the upper and the lower "residue" receivers was closed. All the liquid collected in the lower receiver was run out, after opening it to the atmosphere. It was then closed to the atmosphere and slowly evacuated without disturbing the pressure in the main system.. It was then connected to the upper receiver.

The following readings were noted frequently and maintained constant throughout the test:

(1) Inlet temp. of the heating water;

(2) Outlet ,, ,, ,, ,, ,,

(3) Rate of circulation of hot water as shown by a gauge;

(4) Pressure in the system;

and (5) Temp. of the feed in the feed vessel.

Readings of the temperature drop were started by pushing down the travelling thermocouple to the Tube-Bottom, i.e., to a point on a level with the lowest point of the heated length of the evaporator tube, and throwing the switch on to the"inlet" thermocouple. Successive readings were taken up to half-way up the tube at 1 ft. intervals, and then the switch was thrown on to the"outlet"

thermocouple and readings continued till the travelling thermocouple reached the Tube-Top, ie., the highest point of the heated length of the evaporator tube. The thermocouple was then pushed down gradually and the readings repeated. The mean of the two readings for each position was used in the calculations.

Since the thermocouple was found to have a time-lag of about half-a-minute, the travelling thermocouple was allowed to remain for ½ min. at each position before a reading of the deflection was taken.

At some point in the tube a minimum deflection was found. The thermocouple was moved up and down this position to find the exact value and position of this minimum.

The two traverses of the travelling thermocouple having been made and the minimum deflection and its point of occurrence having been found, the experiment was concluded, and the amount of condensate and residue noted.

Calculations:-

(1) Constants of the Tube. -

Heated length of the tube (distance between the inner ends of the rubber-bungs) = 7ft. 10.5 in.

Outer Diameter = 0.875 in.

Inner ,, = 0.755 in.

Wall Thickness = 0.06 in.

$\therefore$ Mean Diameter = 0.815 in.

$\therefore$ Total Heating Area (based on mean of O.D. & I.D.), $A = \pi \frac{D_o + D_i}{2} \ell$ ft.^{2}

$= \underline{1.681}$ sq. ft.

(2) Δt_m, Δt_{NB} and Δt_B .-

The values of deflections obtained for the various points in the tube were converted to temperature differences in ^oF with the help of the calibration curves. The values of local Δt were plotted against the distance of the respective points from the Tube-Bottom. The points were joined by a smooth curve. The area included between the curve and the axes was divided by the base to obtain the integrated length mean temperature difference Δt_m. The area was obtained by counting squares.

Fig. 1.4 shows some of the typical curves that were thus obtained. It will be noticed that on progressing up from the Tube-Bottom the value of Δt gradually decreases to a minimum and then slowly rises again. Since the temperature of the heating water was nearly constant throughout, these curves follow the temperature of the liquid in the evaporator tube, an approach to a recession

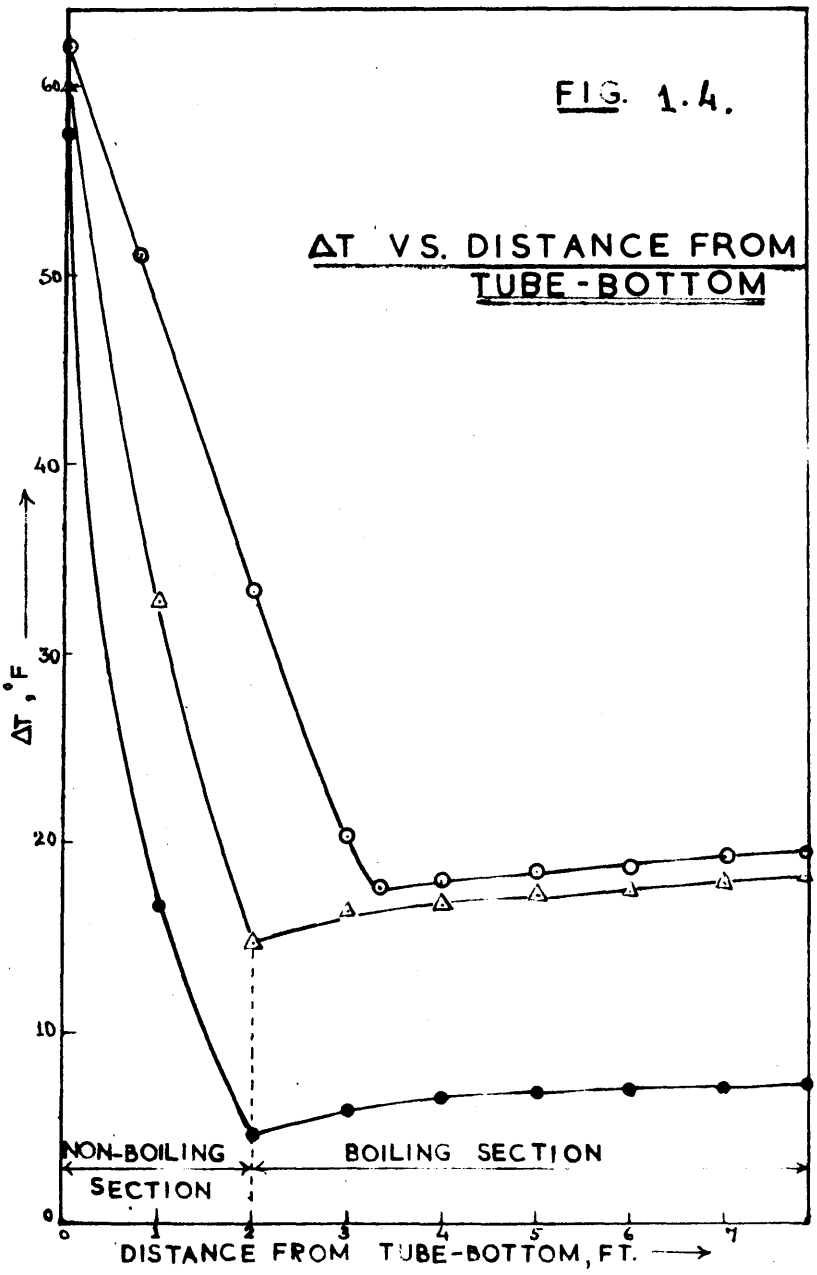


FIG. 1.4.
ΔT VS. DISTANCE FROM TUBE-BOTTOM
60
50
40
30
20
10
0
ΔT, °F
NON-BOILING SECTION
BOILING SECTION
0
1
2
3
4
5
6
7
DISTANCE FROM TUBE-BOTTOM, FT.

from the abscissa indicating an approach to or a recession from the temperature of the heating water in the jacket.

These curves are similar to those of Boarts[46] et al for Temp. Drop vs. Distance from Tube-Bottom. The only difference is that the section after the minimum value of Δt is much grater. These workers (as also Brooks and Badger[44]) attributed the form of the temperature difference curve to a "heating section" in which no boiling occured, followed by a "boiling section" in which the pressure fell steadily giving a lower boiling point, while the liquid boiled steadily as heating proceeded. An advantage of the glass-tube was that it was noted, with certain reservations to be discussed later, that this was the state of the liquid vapour mixture in the tube and that the point of minimum Δt agreed roughly with the start of boiling.

The minimum point in the curve was taken to correspond to the maximum temperature of the liquid and also to serve as a boundary between the Non-Boiling (or, Heating) and the Boiling Sections of the tube. The length mean temperature drop for each section, therefore, was found by counting the squares in the particular section and dividing by the part of the base corresponding to that particular section. In this way Δt_{NB} and Δt_{B} were found for the Non-Boiling and Boiling Sections, respectively.

(3) The Boiling and Non-Boiling Areas.-

The areas of the non-boiling and boiling sections were computed by taking the length of the non-boiling section as the distance between the Tube-Bottom and the Point of Maximum Temp. of the Liquid in the Tube (i.e., the point of minimum deflection), and the rest of the heated length of the tube as that for calculating the Boiling Area.

(4)"Residue" and "Condensate" -

The amount of "condensate" during the period of test was converted to hourly rate. This hourly rate was multiplied by the appropriate density factor to obtain it in lbs/hr. This gave the Evaporation in lbs/hr.

Similarly, the amount of "Residue" was converted to lbs/hr.

The total of Evaporation in lbs/hr and the "Residue" in lbs/hr gave the Feed Rate in lbs/hr.

(5) Heat Load, q, per hour:-

(a) The product of Evaporation (in lbs/hr) and the Latent Heat of the liquid at its Tube-Top temperature gave the total heat to vapour.

Thus,

Heat to vapour = Evaporation x Latent Heat.

The Tube-Top Temperature was found by subtract-

ing the value of Δt at Tube-Top from the temperature of heating water at outlet.

The Latent heat of vaporisation for water was read from Steam-Tables.

The Latent Heats for Ethyl Alcohol and Toluene were read from their respective curves [Figs.5·3, and 5·31 , respectively , in Chapter V of this work].

(b) The amount of heat required to raise the total feed from its initial temp. in the feed vessel (or, at the Tube-Bottom) to the temperature existing at Tube-Top was found as follows:-

Heat to Liquid = Feed Rate x [Tube-Top Temp. - Initial Temp.] x Sp.Heat.

This Sp. heat was taken at the mean of the initial and Tube-Top temperatures of the feed.

In the case of water and 0.1 perc. Aqueous solution of "Perminal W.A." this Sp. heat was always taken as unity.

The Sp. heat of Ethyl Alcohol (95.6 % . by weight) used in the present work was taken to be the same as that for 95 %. Ethyl Alcohol. Both this and the Sp. heat for Toluene were computed from the nomograph given in Ref.3, p.401. Then, Total Heat Load per hour, (q) = Heat to vapour + Heat to liquid.

= (a) + (b)

(6) Heat Loads q_{NB} and q_B per hour:-

These were found as follows:-

The amount of heat that is taken by the vapour in the form of latent heat does not all come from the Boiling section. For some of this heat is given out by the superheated lquid as it flashes to vapour in the Boiling section

Now, the heat to Maximum temp. of feed is all transmitted through the non-boiling section;,therefore, heat to maxm. temp.,

q_{NB} = Feed Rate × [Maxm temp. - Initial temp.] x Sp.heat

This Sp.heat was taken, as before, at the mean of the initial and the maximum temperatures of the feed.

The Maximum Liquid Temperature was found by subtracting the minimum Δt from the temperature of heating water at inlet, since at the point of minimum Δt the travelling thermocouple was usually compared with the "inlet" thermocouple. In some instances, however, the "outlet" thermocouple was used, and in these the minimum Δt was subtracted from the temp. of heating water at outlet to get the maximum feed temperature.

Then, the heat load through the boiling section, q_B,

= Total heat load - Heat to maxm. temp.

or,

$$q_B = [q - q_{NB}]$$

(7) Overall Heat Transfer Coefficients:-

These were then evaluated as follows:-

(i) Entire Tube:-

$$U = \frac{q}{A \times \Delta t_m}$$

(ii) Non-Boiling Section:-

$$U_{NB} = \frac{q_{NB}}{\text{Non-boiling area} \times \Delta t_{NB}}$$

(iii) Boiling Section:-

$$U_B = \frac{q_B}{\text{Boiling Area} \times \Delta t_B}$$

A Sample Calculation:-

Liquid :- 95.6 percent Ethyl Alcohol.

Test No. 1, TABLE 1.21

Duration of test ..... = 36 min.

Condensate = (2.23 - 0.70) litres = 1.53 litres

Residue = (4.61 - 0.21) ,, = 4.40 litres

$$\therefore \text{Evaporation} = \frac{1.53 \times 1000 \times 0.7936 \times 60}{36 \times 453.6} = 4.46 \text{ lbs/hr.}$$

$$\text{Residue} = \frac{4.40 \times 1000 \times 0.7808 \times 60}{453.6 \times 36} = 12.62 \text{ lbs/hr.}$$

$\therefore$ Feed Rate = 17.08 ,, ,,

Densities of Ethyl Alcohol (95.6%) at the temp. of the liquid at the time of measuring its volume.

Initial Feed Temp. .....= 61.9°F.

Temperature of heating water, Inlet.= 50°C.

" " " " Outlet.= 49.9°C.

Δt at Tube-Top.....= 10.5°C.

Minimum Δt .....= 7.0°C.

Δt_{NB} .....= 31.2°F.

Δt_B .....= 16.9°F.

Non-Boiling Length .....= 2.0 ft.

Boiling Length .....= 5.875 ft.

Δt_m .....= 20.7°F.

∴ Non-Boiling Area .....=(π x 0.815 x 2)sq.ft.

= 0.427 sq.ft.

Boiling Area .....=(π x 0.815 x 5.875)sq.ft.

= 1.254 sq.ft.

Tube-Top Temp. = (49.9 - 10.5)c.....= 39.4°C.

= 102.9°F.

Maxm. Temp. of Feed = (50.0 - 7.0)c.= 43°C.

= 109.4°F.

Latent Heat of vaporisation at 102.9°F. (as found from Fig.5.3) is 417.5 B.Th.U/lb.

∴ Heat to vapour .....=(4.46 x 417.5)B.Th.U./hr.

= 1862 " " " "

Heat to Tube-Top Temp.of Liquid = 17.08(102.9-61.9)x0.661 B.Th.U./hr.

= 463 B.Th.U./hr.

$\therefore q = (1862 + 463) \ldots\ldots = 2325$ B.Th.U./hr.

$\therefore U = \frac{2325}{1.681 \times 20.7} = \underline{66.9}$ B.Th.U./hr./sq.ft/^{o}F.

Now,

Heat to maximum temperature

$= 17.08(109.4-61.9) \times 0.669$ B.Th.U/hr.

$= 543$ B.Th.U./hr.

$\therefore q_{NB} \ldots\ldots\ldots\ldots\ldots = 543$ B.Th.U./hr.

$\therefore q_{B} = (2325 - 543) \ldots\ldots = 1782$ B.Th.U./hr

$\therefore U_{NB} = \frac{543}{31.2 \times 0.427} = 40.7$ B.Th.U./hr./sq.ft/^{o}F.

& $U_{B} = \frac{1782}{16.9 \times 1.254} = 84.2$ B.Th.U./hr./sq.ft/^{o}F.

.....

Results:-

These are tabulated in the Tables that follow. As already indicated, the following liquids have been used:-

(1) Water,

(2) 0.1 % ,, "Perminal W.A." solution in water,

(3) 95.6 ,, (by-Weight) Ethyl Alcohol, and

(4) Nitration Quality Toluene.

.....

T A B L E . 1.1

WATER IN GLASS-TUBE EVAPORATOR. (TABLE. 1.1.)

Temp. of Heating Water 80°C.

Total Heat Transfer Area = 1.681 sq.ft.

Test No.	Feed Rate (lbs/hr)	Evapo-ration (lbs/hr)	Evapo-ration %	Initial Liquid Temp. °F	Tube-Top Temp. °F	Max. Liquid Temp. °F	q	Δt_m °F	U	q_B	Boiling Area. sq.ft.	Δt_B °F	U_B
1.	10.995	5.64	51.35	62.6	136.4	143.6	6532	39.1	99.5	5642	1.431	34.6	114.0
2.	13.820	5.72	41.42	63.3	137.7	144.1	6853	39.1	104.0	5734	1.396	34.6	118.8
3.	16.830	5.35	31.82	65.7	138.8	145.2	6660	39.5	100.5	5322	1.325	33.7	119.2
4.	21.480	5.08	23.67	65.3	139.3	144.7	6743	39.9	100.5	5038	1.272	33.4	118.6
5.	23.315	5.36	22.98	71.3	137.7	145.8	6977	40.5	102.5	5240	1.272	33.8	122.0
6.	23.350	5.23	22.40	54.2	137.7	143.8	7260	41.8	103.0	5168	1.254	34.8	118.5
7.	34.750	4.88	14.05	70.4	137.7	146.0	7288	42.1	103.0	4663	1.130	33.9	121.8
8.	37.790	4.77	12.62	69.8	137.7	145.6	7405	43.5	101.5	4542	1.112	34.2	119.5
9.	39.875	3.97	9.96	56.3	139.5	143.1	7343	43.1	101.5	3881	0.987	33.7	116.5
10.	41.200	4.50	10.93	69.4	138.8	146.0	7430	43.8	101.0	4275	1.056	33.5	120.9

T A B L E . 1.12.

WATER IN GLASS-TUBE EVAPORATOR.

Heating Water at 80°C.

Total Heat Transfer Area = 1.681 sq.ft.

(TABLE. 1.12.)

Boiling Area ... ... = 1.254 sq.ft. in all tests.

Non-Boiling Area ... = 0.427 " " " " "

Test No.	Feed Rate lbs/hr	Evapo-ration lbs/hr	Evapo-ration %	Initial Liquid Temp. °F	Tube-Top Temp. °F	Max. Liquid Temp. °F	q	Δt_m °F	U	q_{NB}	Δt_{NB} °F	U_{NB}	q_B	Δt_B °F	U_B
1.	11.74	1.324	11.3	62.1	164.9	170.8	2532	15.42	98.0	1276	31.24	96.0	1256	9.53	105
2.	11.72	1.368	11.7	62.3	164.4	169.9	2567	16.00	95.5	1260	31.70	93.0	1307	10.05	104
3.	12.91	1.602	12.4	70.7	162.4	167.7	2789	17.41	95.5	1232	36.37	81.0	1537	11.88	103.5
4.	16.75	2.315	13.2	67.1	157.2	163.3	3835	25.17	90.5	1614	49.15	77.0	2221	16.82	105.5
5.	16.45	2.406	14.6	63.0	157.2	161.8	3968	25.30	93.5	1625	49.15	77.5	2343	16.88	111
6.	18.48	3.004	16.3	66.4	152.5	158.0	4617	29.48	93.5	1694	53.30	74.5	2925	21.73	107.5
7.	18.63	2.950	15.8	66.6	152.7	157.8	4795	29.96	95.5	1699	54.00	74.0	3060	21.58	113
8.	18.77	3.345	17.8	63.0	149.6	155.8	4999	32.33	92.0	1742	55.55	73.5	3257	24.12	108
9.	20.50	3.675	17.9	68.4	148.6	154.4	5354	32.68	97.5	1746	54.75	75.5	3590	24.10	119
10.	21.12	3.675	17.4	66.2	148.5	154.6	5448	33.65	96.5	1866	57.10	76.5	3582	25.36	113
11.	26.92	4.713	17.5	65.0	142.5	149.4	6866	38.93	105.0	2265	61.58	86.0	4601	30.63	120
12.	25.81	4.660	18.6	64.4	142.5	149.2	6735	39.10	102.5	2265	61.20	87.0	4470	31.62	113

T A B L E . 1.13.

0.1 % AQ. SOLUTION OF "PERMINAL W.A." IN GLASS-TUBE EVAPORATOR.

Heating Water at 80°C.

Total Heat Transfer Area = 1.681 sq.ft.

(TABLE. 1.13.)

Test No.	Feed Rate lbs/hr	Evapo-ration lbs/hr	Evapo-ration %	Initial Liquid Temp. °F	Tube-Top Temp. °F	Max. Liquid Temp. °F	q	Δt_m °F	U	q_B	Boiling Area. sq.ft.	Δt_B °F	U_B
1.	13.17	5.68	43.15	60.70	140.7	144.3	6804	37.0	109.5	5703	1.414	32.7	123.5
2.	14.85	5.87	39.55	81.85	140.9	144.3	6818	36.5	111.5	5892	1.414	32.4	128.5
3.	21.59	5.29	24.53	79.35	140.5	143.6	6678	37.9	105.1	5292	1.289	33.1	124.0
4.	26.13	4.98	19.06	77.90	140.5	143.6	6681	40.0	98.5	4965	1.218	33.2	122.8
5.	28.94	4.79	16.54	68.20	140.9	144.8	6955	42.8	97.0	4738	1.146	32.6	126.8
6.	33.70	4.58	13.61	68.00	140.5	146.0	7087	43.8	96.5	4462	1.077	32.3	128.3
7.	42.08	3.93	9.34	66.20	138.9	143.9	7033	48.2	87.0	3766	0.952	33.9	116.6

T A B L E . 1.2.

ETHYL ALCOHOL (95.6 %) IN
GLASS-TUBE EVAPORATOR.
Heating Water at 50°C.
Total Heat Transfer Area = 1.681 ft.²

(TABLE. 1.2)

Test No.	Feed Rate lbs/hr	Evapo-ration lbs/hr	Evapo-ration %	Initial Liquid Temp. °F	Tube-Top Temp. °F	Max. Liquid Temp. °F	q	Δt_m °F	U	q_B	Boiling Area. sq.ft.	Δt_B	U_B
1.	6.09	3.216	52.8	72.9	106.7	115.7	1491	14.2	62.5	1312	1.361	12.1	79.7
2.	6.47	3.112	48.1	73.0	105.6	113.4	1453	14.7	58.8	1274	1.451	13.3	67.0
3.	7.75	3.145	40.6	71.6	106.5	114.8	1499	14.9	59.9	1270	1.325	11.4	84.2
4.	7.78	2.972	38.2	71.3	106.2	114.6	1425	15.5	54.7	1194	1.325	12.5	71.9
5.	8.31	3.288	39.6	69.8	107.1	116.2	1576	14.4	65.1	1312	1.361	11.5	84.0
6.	8.44	3.250	38.5	65.9	106.5	114.8	1590	14.6	64.9	1308	1.378	11.9	79.8
7.	11.11	3.008	27.1	66.2	106.2	114.6	1566	15.1	61.8	1198	1.201	12.7	79.0
8.	13.39	2.770	20.7	64.4	106.2	114.7	1536	17.5	52.2	1081	1.146	12.0	78.8
9.	13.91	3.007	21.6	69.8	106.3	114.1	1605	15.7	60.9	1184	1.201	12.2	81.0
10.	31.62	2.446	7.70	64.0	106.0	111.5	1911	19.6	57.7	900	1.005	12.6	70.9

T A B L E . 1.21.

ETHYL ALCOHOL (95.6 %) in

GLASS-TUBE EVAPORATOR.

Heating Water at 50°C in Tests 1 to 5, and at 80°C in the rest of them. Total Heat Transfer Area = 1.681 ft.²

(TABLE. 1.21.)

Boiling Area ... ... = 1.254 sq.ft. in all tests.

Non-Boiling Area ... = 0.427 " " " " "

Test No.	Feed Rate lbs/hr	Evapo-ration lbs/hr	Evapo-ration %	Initial Liquid Temp. °F	Tube-Top Temp. °F	Max. Liquid Temp. °F	q	Δt_m °F	U	q_{NB}	Δt_{NB} °F	U_{NB}	q_B	Δt_B °F	U_B
1.	17.08	4.46	26.1	61.9	102.9	109.4	2325	20.7	66.9	545	31.2	40.7	1782	16.9	84.2
2.	18.57	4.45	23.9	63.5	102.2	108.7	2301	21.1	64.9	495	30.6	38.0	1806	17.7	81.6
3.	16.67	4.67	28.1	60.3	101.9	108.0	2374	21.7	65.1	477	32.2	34.8	1879	17.9	84.6
4.	20.54	4.97	24.2	68.7	100.6	107.4	2483	22.2	66.6	485	30.8	37.0	1998	18.9	84.4
5.	19.06	4.95	26.0	66.8	100.6	106.0	2462	22.8	64.2	455	32.0	33.5	2007	19.3	83.0
6.	20.10	5.06	25.1	83.9	156.2	158.3	2951	25.2	68.8	1016	45.6	52.5	1935	18.7	82.4
7.	20.31	5.25	25.9	77.4	156.6	159.2	3224	26.5	72.4	1118	51.2	51.0	2106	18.2	92.3
8.	18.35	5.15	28.2	64.9	157.1	158.3	3223	27.1	70.8	1130	52.8	50.0	2093	18.5	90.5
9.	19.78	5.15	26.1	71.6	154.2	158.0	3193	28.6	66.5	1142	52.9	50.5	2051	20.4	80.4
10.	19.04	5.46	28.7	76.2	154.0	157.3	3240	28.8	67.0	1035	51.0	47.5	2205	20.8	84.6
11.	21.35	6.65	31.2	78.8	151.5	154.8	3766	30.6	73.3	1087	51.9	49.0	2679	23.2	92.8
12.	18.77	6.83	36.4	65.3	150.8	153.6	3845	32.0	71.6	1087	53.8	47.5	2758	23.9	92.3
13.	24.55	8.26	33.7	73.4	145.2	148.7	4563	36.9	73.6	1220	58.7	48.5	3343	29.5	90.6
14.	19.65	8.27	42.1	65.3	146.0	150.1	4365	37.0	70.2	1083	58.7	44.0	3282	28.6	91.6
15.	29.46	7.75	26.3	71.6	146.7	148.8	4641	37.0	74.7	1494	61.4	57.0	3167	28.0	90.5

CHAPTER. I.

(TABLE 1.3)

T A B L E . 1.3.

TOLUENE IN GLASS TUBE EVAPORATOR.

Heating Water at 80°C.

Total Heat Transfer Area = 1681 ft.^{2}

Test No.	Feed Rate lbs/hr	Evaporation lbs/hr	Evaporation %	Initial Liquid Temp. °F	Tube-Top Temp. °F	Max. Liquid Temp. °F	q	Δt_m °F	U	q_B	Boiling Area sq.ft.	Δt_B °F	U_B
1.	28.88	13.60	47.1	68.0	154.9	157.5	3334	24.1	82.5	2197	1.218	19.2	94.0
2.	31.06	13.74	44.3	68.0	155.1	157.6	3439	24.5	83.8	2215	1.218	18.8	97.0
3.	31.64	13.85	43.8	68.5	154.7	157.1	3460	25.5	80.6	2238	1.193	19.4	97.2
4.	34.29	14.00	40.8	68.4	155.3	157.3	3599	25.1	85.3	2259	1.146	19.0	103.8
5.	34.48	14.81	43.0	70.5	152.6	154.9	3670	27.5	79.5	2391	1.182	21.3	95.0
6.	35.51	13.39	37.7	68.7	155.3	157.1	3531	26.4	79.5	2150	1.094	19.4	101.4
7.	41.88	13.84	33.1	66.2	156.2	159.6	3915	26.8	86.9	2195	1.146	17.7	106.1
8.	44.10	13.50	30.6	69.2	156.8	157.7	3986	27.3	87.1	2272	1.041	17.9	122.0
9.	59.38	14.83	25.0	66.2	153.6	156.6	4687	32.1	87.0	2379	0.934	19.9	127.8

Observations on the Nature of Boiling.

In the present investigations with the glass tube evaporator the behaviour of the liquid inside the tube could easily be seen.

It was found that the liquid system could be divided into the non-boiling and the boiling sections. The liquid column rose slowly up the tube rising in temperature till it attained a maximum. At this region marked boiling began.

Nature of Boiling when Air leaked into the Tube:-

As soon as the feed enters the tube, small bubbles begin to rise along with it. They gradually grow in size as they ascend higher in the liquid column, due to the release in the pressure. There is no apparent turbulence in the liquid except that caused by these rising bubbles of air. The air bubbles are almost flat in the beginning. But as they ascend higher they move faster and become longer - up to ½ inch. As they reach the zone where boiling commences they lengthen rapidly to 3 - 4 inches, and then merge into the rising column of vapour.

Under a given vacuum, the level at which boiling commences depends upon the initial feed temperature, and the feed rate. With a larger feed rate or lower feed temp.

a longer length of the tube is required for boiling to begin.

There is no distinct separation of the non-boiling and the boiling sections as the boiling never takes place sharply. The two sections merge into each other and this lack of a definite boundary is accentuated by the air bubbles.

The nature of boiling is interesting. Towards the top of the liquid column bubbles of vapour begin to appear and within a few inches assume vigorous formation. Besides the air bubbles coming from the bottom, some also arise from the side of the tube and all these merge into the froth which occupies a certain length of the tube. The distribution of vapour and liquid in this region is more or less uniform. The evolution of bubbles, however, is not steady, but keeps fluctuating. Each big bubble of air causes a maximum "flash" - a sudden evolution of a swarm of bubbles. This appears to correspond to situation (1),(see Introduction, p.60).

On going higher, the froth resolves itself into a mixture of liquid and vapour, the distribution of the two phases being by no means uniform. The vapour is seen to push its way up in a zig-zag manner through the liquid, carrying slugs of the latter along with it. This corresponds with situation (2), except for the lack of uniformity in the distibution of the two phases.

Still higher, the vapour gets released in the centre of the tube and moves rapidly up still dragging the liquid along with it. The liquid moves along the sides of the tube in the form of "rings". These rings meet another stream of rings coming downwards from the top of the tube, so that their density in some regions increases. These rings keep rising and falling at a rapid rate. At short intervals a column of vapour and liquid rings, forced up by a large bubble of air which momentarily causes a flash, strikes against the rubber bung supporting the travelling thermocouple pocket. The vapour and some of the liquid having escaped through the side tube, the remaining liquid begins to drain down the sides of the tube in the form of rings which are again hurled up by a fresh volley of rising vapour and liquid rings. As the rings move up and down, they become denser in some regions and sparser in others. The position of these regions is by no means fixed. The appearance thus presents a very rough pattern of a stationary wave, the vibrating elements in this case being the liquid rings. This corresponds to situation (3).

During the interval between volleys of liquid rings and vapour coming and striking against the rubber bung at the top, a coarse spray is seen at the top, the droplets moving rather slowly and falling on to the sides of the tube or else striking against the rubber bung.

But no fine spray is to be seen.

Under steady conditions all the liquid fed at the bottom escapes as liquid and vapour from the top of the tube through the side-arm. There is always a definite amount of liquid and vapour in the tube, the quantity depending upon the feed rate, Δt_m, pressure, etc. That surface tension plays an important role in the phenomena observed above seems very probable.

EFFECT OF DEAERATION ON THE NATURE OF BOILING.

In the absence of all air the liquid rose into the tube without boiling commencing at the level where it should have done under the prevailing conditions. When it reached a point in the tube where there was an irregularity in the surface, violent boiling began. The liquid, thus, underwent excessive superheating. This was chiefly noticeable in the case of toluene and alcohol.

To obviate it, a very slight leakage of air was allowed at the ground-glass joint of the flow-regulator and the evaporator tube. From here tiny bubbles of air arose at irregular intervals. Some bubbles formed on the sides of the tube also in the non-boiling section. These prevented the liquid from abnormal superheating, without much interfering with the natural convection of the liquid

in the non-boiling section.

At high feed rates gradual boiling set in. There was no clear boundary between the heating and the boiling sections. Boiling was rather steady with a very little tendency to "flash".

At low feed rates, however, "flashing" was more pronounced because of the higher hydrostatic head causing greater superheating. This tendency was mitigated by the leaking air bubbles. The boundary between heating and boiling sections was clearer than with the aerated liquid. On the whole, therefore, the appearance of boiling did not undergo any essential change on lowering the feed rate.

The effect of the up and down movement of the liquid in the boiling section is transmitted to a small extent to the liquid in the heating section as evidenced by the appearance of the convection currents. Tiny pieces of rubber introduced into the fluid stream showed this oscillation clearly. This phenomenon is to be seen with or without deaeration.

EFFECT OF REDUCED SURFACE TENSION ON BOILING.

Fritz and others (cited by Ref. 45) showed that a decrease in surface tension

reduces the maximum size of the vapour bubbles. Stroebe et al held that wettability of the surface is an important factor in boiling. It governs the size and the shape of the bubbles and the rate at which they are evolved from the heating surface.

In the present investigations almost microscopic bubbles rose from the bottom. Their number multiplied as the liquid rose up the tube. At some zone boiling set in with distinct separation of heating and boilin sections. The tiny bubbles arising from below joined the main stream which, once shot up, never returned. The intensity of the evolution of bubbles varied regularly. There were "flashes" at short intervals, the formation passing from a maximum at the beginning of a flash to a minimum just preceding the next. The bubbles arose from the liquid surface along the entire cross-section of the tube; so that one could say with exactitude where the boiling commenced. The boundary between Heating and Boiling sections was clearly defined.

With each flash a swarm of bubbles shot to the top of the tube and escaped through the side-tube. The rate of evolution of bubbles gradually fell after each flash. When the bubbles became less numerous, they could be seen rising up the tube in the form of flat discs. The sides of the tube remained wet throughout with an

uneven but thin film of liquid on them - very much thinner than that obtained with the pure liquids.

EFFECT OF Δt_m ON THE NATURE OF BOILING.

Over the range of low values of Δt_m observed, in the case of ethyl alcohol and water, it was found that there was no great change in the nature of boiling except that, in the case of water, the frothy region (situation 1) almost disappeared, obviously because under these conditions the vigour of boiling became subdued. The boiling region, therefore, consisted of a region of slug action and a region of film action (situations 2 and 3; see Introduction, p. 60).

Since the region of froth (i.e., situation 1) disappeared at low Δt_m, it would seem that for stability of bubbles, either the surface tension should be low or else there should be a larger Δt_m to give larger superheat and more vigorous boiling so that stable bubbles form. The slug action is obviously due to bubble coalescence and this becomes more pronounced in Situation (3) where the vapour forms one continuous column and where the vigour of boiling is most pronounced.

.....

FIG. III. DEAERATING FEEDER.

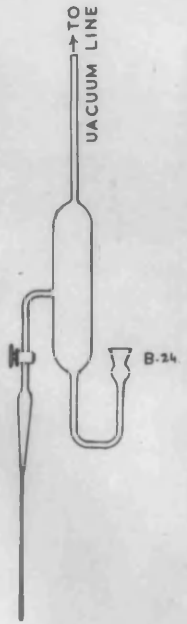
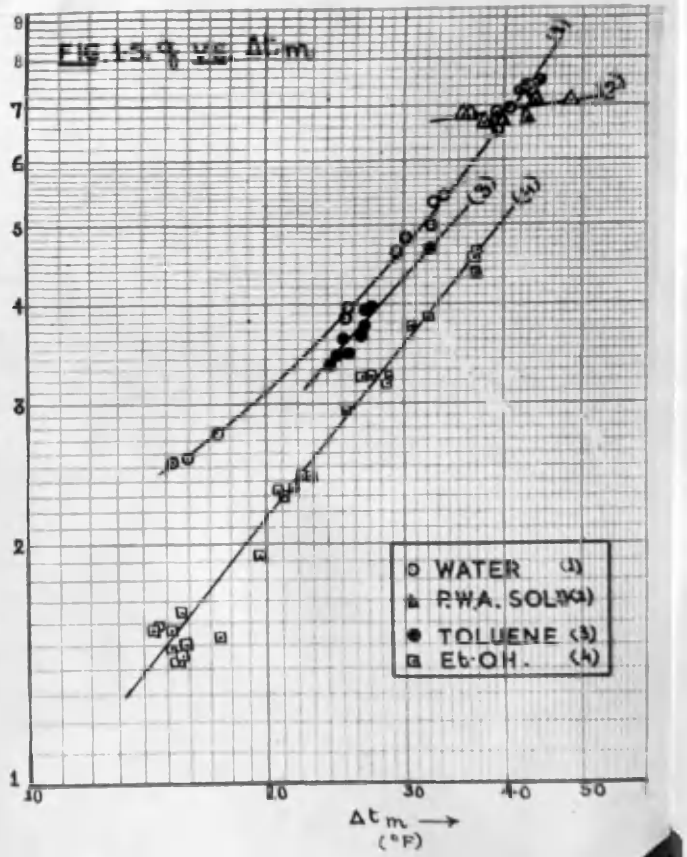


FIG. 15. q_0 VS. Δt_m



CORRELATIONS

A preliminary examination of the tables showed a confused variation of Hourly Heat Load, (q), with Feed Rate and Δt_m. A change in Δt_m caused both "q" and the amount of vaporisation to alter. However, "q" was plotted against Δt_m on log-log paper (Fig. 1.5) for all the liquids. Except for pure water the curves are very nearly straight lines. The lines for Ethyl Alcohol and Toluene have an average slope of 1.19, so that, for these two liquids

$$q \propto (\Delta t_m)^{1.19} \quad \ldots \quad \ldots \quad \ldots \quad (1.1)$$

For each series of tests a plot of "q" vs. Feed Rate gave a separate curve, each having a different slope (Fig. 1.7).

A plot of U_B vs. Evaporation (lbs/hr), (Fig.1.9), showed that the points for water and Aqueous solution of Perminal W.A. could be correlated by a single line with a very small slope. The curve for ethyl alcohol has a much larger slope. Thus,

for water, $$U_B \propto (Ev.)^{0.11} \quad \ldots \quad \ldots \quad (1.2)$$

and

for Et.OH, $$U_B \propto (Ev.)^{0.27} \quad \ldots \quad \ldots \quad (1.3)$$

where Ev. = Evaporation in lbs/hr.

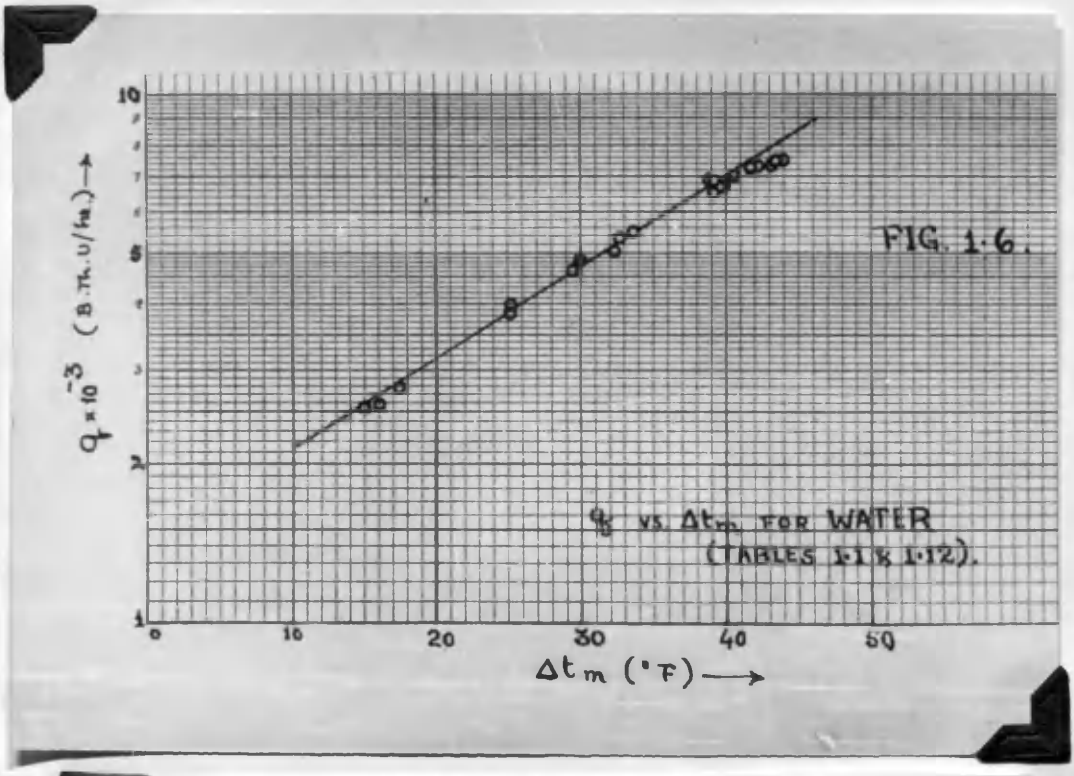
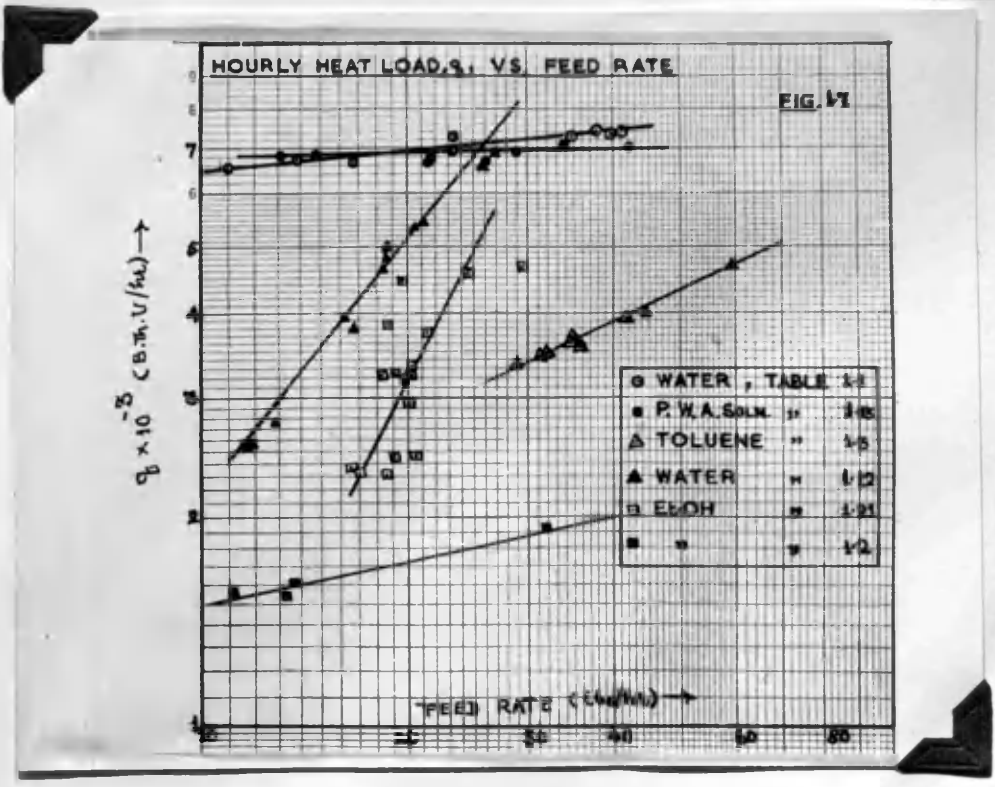


FIG. 1.6.
$q_f \times 10^{-3}$ (B.Th.U/hr.) →
q_f vs. Δt_m FOR WATER
(TABLES 1.1 & 1.12).
Δt_m (°F) →


HOURLY HEAT LOAD, q_f VS. FEED RATE
FIG. 1.7
$q_f \times 10^{-3}$ (B.Th.U/hr.) →
WATER, TABLE 1.1
P.W.A. SOLN. " 1.15
TOLUENE " 1.5
WATER " 1.12
EtOH " 1.21
" " 1.2
FEED RATE (Lbs/hr.) →

In the case of toluene where the amount of vapour formed per hour did not much vary, the points are mostly coincident and lie vertically one above the other. A plot of U_B vs. Feed Rate (Fig. 1.91) for all liquids gave several curves but in no case was the slope considerable except in the case of Toluene, for which

$$U_B \propto (\text{Feed Rate})^{0.4} \quad \ldots \quad \ldots \quad \ldots \quad (1.4)$$

Only in the case of water and ethyl alcohol there was a variation in Δt_B. A plot of U_B vs. Δt_B (Fig. 1.8) for these two liquids gave a separate curve for each. The two lines are almost parallel with an average slope of 0.12, so that

$$U_B \propto (\Delta t_B)^{0.12} \quad \ldots \quad \ldots \quad \ldots \quad (1.5)$$

for either liquid.

For water, q vs. Δt_m on a semilog paper (Fig.1.6) gave a curve with the following equation:-

$$\log q = 3.1058 + 0.01832\, \Delta t_m \quad \ldots \quad (1.6)$$

.....

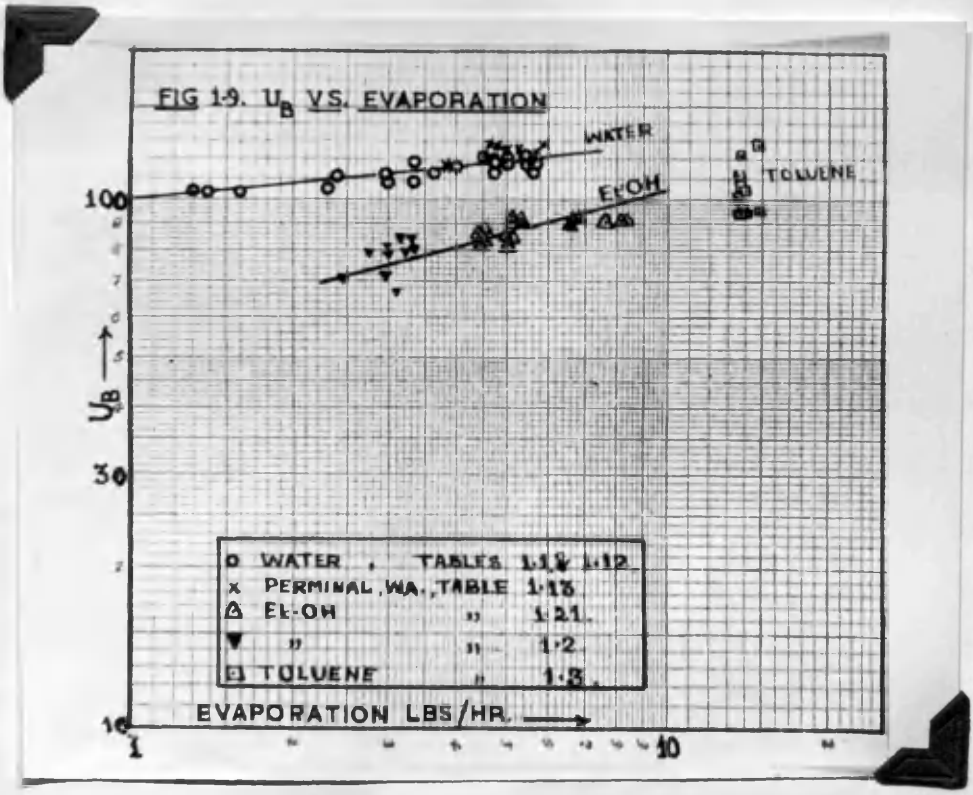


FIG 1.9. U_B VS. EVAPORATION
WATER
ETOH
TOLUENE
U_B →
100
30
10
1
10
EVAPORATION LBS/HR. →
o WATER , TABLES 1.1 & 1.12
x PERMINAL, WA., TABLE 1.13
Δ Et-OH " 1.21.
▼ " " 1.2
⊡ TOLUENE " 1.3.

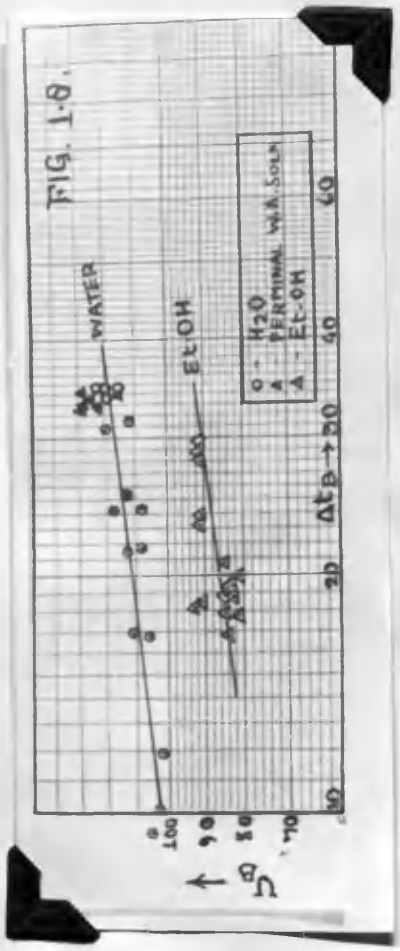


FIG. 1.8.
WATER
Et·OH
o - H2O
Δ - PERMINAL W.A. SOLN
▲ - Et-OH
U_B →
Δt_B → 30
40
60
70
80
90
100

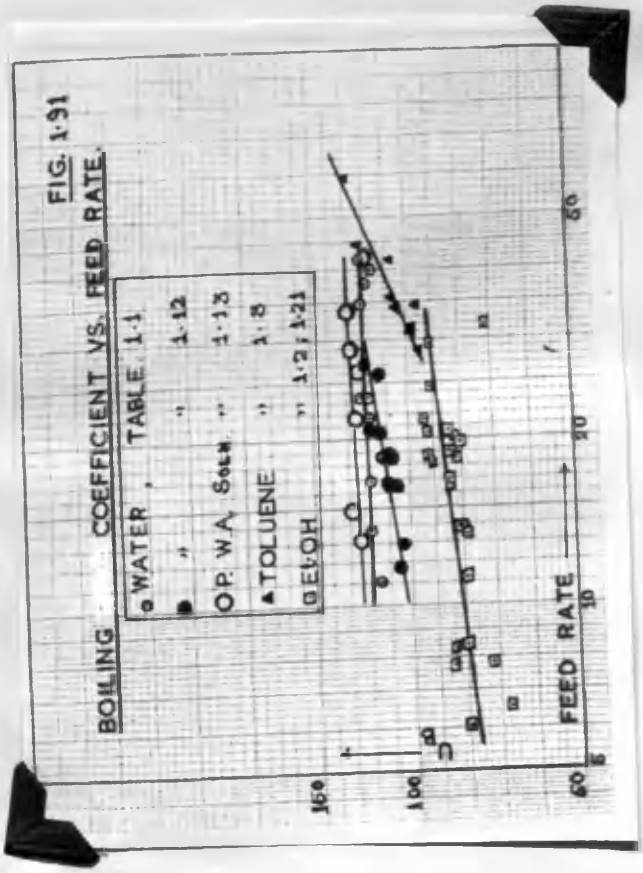


FIG. 1·91
BOILING COEFFICIENT VS. FEED RATE.
o WATER, TABLE 1·1
" " 1·12
⊙ P. W.A. SOLN " 1·13
▲ TOLUENE " 1·3
⊡ Et·OH " 1·2; 1·21
FEED RATE →
160
100
60
10
20
30
40
50
60

DISCUSSION

The most important fact that comes out of these graphical correlations is that Δt_m is by far the most effective variable, apart from, of course, the nature of the liquid. It controls both the heat flux and the coefficient of heat transfer. When the mean temperature drop is roughly constant from test to test, feed rate has very slight effect on the value of heat flux. However, in the case of 0.1 per cent aqueous solution of Perminal W.A., variation in Δt_m did not have any considerable effect on the value of "q", the hourly heat load (Fig.1.5). This is a striking result and more data are necessary to confirm it.

If, however, Δt_m varies, the heat flux also varies steadily with it for all liquids except in the case of Perminal W.A.-solution as noted above. With varying mean temp.drop, a variation in the feed rate affects flux for water and ethyl alcohol much more than that for toluene (Fig. 1.7). In the case of toluene (Table 1.3)the mean temp. drop, Δt_B, for the boiling section was roughly constant and the variation in the amount of vapour formed per hour was small. The effect of an increase in the feed rate would, therefore, be to increase the velocity of the

fluid through the tube giving a higher flux (Fig.1.7), and higher U_B (Fig.1.91). In the case of ethyl alcohol and water, an increase in Δt_m was accompanied by an increase in the amount of evaporation (Tables 1.12 and 1.21) and, therefore, although the feed rate was altered considerably, the former rather than the latter (see Figs.1.9 and 1.91) had the more important effect on the Boiling Overall Coefficient, U_B.

For a given mean temp. drop and Feed Rate, the values of hourly heat load (q) are the highest for water, intermediate for toluene and the lowest for ethyl alcohol. For similar values of Δt_B, the magnitudes of U_B, the boiling overall coefficient, for the three liquids, are similarly related. The effect of reduced surface tension has been to give somewhat higher boiling coeffs. than for pure water (see Figs. 1.8, 1.9 and 1.91), although the high resistance of the glass-tube wall has had a great obscuring effect. This increase in U_B with decrease in Surface Tension is as should be.

The higher values of U and U_B for Toluene than those for Ethyl Alcohol, for similar values of Δt_m and Δt_B, repectively, are somewhat unexpected. This may be partly due to the fact that in the case of toluene a much larger molar fraction was vaporised than in the case of

ethyl alcohol. The higher molar fraction evaporated must have induced higher velocities, giving better heat transfer. A similar result has been found with the Copper Tube Evaporator (CH. II). Variation in feed rate has not affected q_B for toluene, for q_B depends primarily upon the amount of vapour formed which has remained practically unchanged.

The velocity in the boiling section is contributed by both the liquid and the vapour. When the percentage evaporation is high the effect of the vapour predominates and the values of coeffs. are high. With increasing feed rate, vaporisation decreases somewhat and so do the coefficients. At high feed rates, when the amount of vapour diminishes, it appears, the deficiency is made up by the liquid. Also, observations on the nature of boiling showed that, with high feed rates, there was much agitation in the boiling liquid. This might have a tendency to reduce the thickness of the liquid film and give better heat transmission.

.....

C H A P T E R. II.

THE METAL-TUBE, VERTICAL, NATURAL-CIRCULATION, EVAPORATORS.

CHAPTER II.

THE METAL TUBE, VERTICAL, NATURAL-CIRCULATION, EVAPORATORS.

The purpose of the work on the glass-tube evaporator was mainly intended to investigate the theory that the tube could be divided into boiling and non-boiling sections. For a glass-tube evaporator, this seemed to be substantiated, and work was taken up on metal-tube evaporators. The preliminary work was done on a Stainless Steel Tube, using water under natural-circulation. The apparatus (Fig.2.1) was the same as had been used previously in these laboratories (Ref.59). The evaporator tube (Stainless Steel, Specn., STAYBRITE, F.M.B.) was about 10 ft. long by 0.5 in. i.d. by 0.7 in. o.d., heated for 9 ft. 2 in. of its length by hot water circulating through its jacket of iron pipe ($1\frac{3}{8}$ in. o.d. x 1 in. i.d.) with iron T-pieces at either end. These latter acted as inlet and outlet for heating water and had thermopockets provided on them. Two brass stuffing boxes, each with a cap and a gland nut, fixed to the top and bottom of the jacket and packed with asbestos cord, served to hold the evaporator tube in position. The evaporator tube was screwed into a brass gland-

NATURAL CIRCULATION EVAPORATOR.

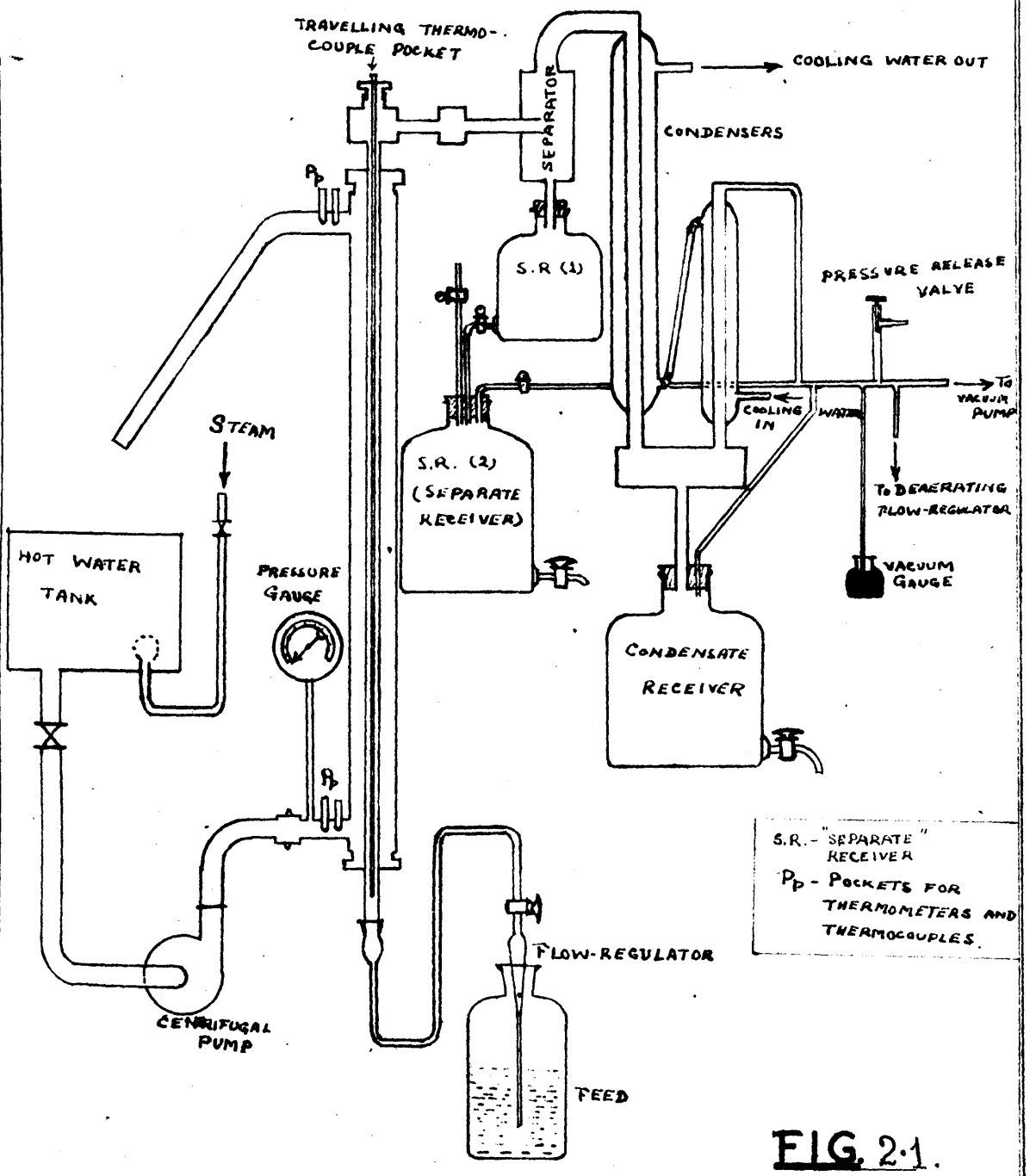


FIG. 2·1.

piece at the top. This gland-piece had a side-arm which could be connected to that of the separator. It also had a stuffing-box and gland-nut provided for holding the travelling thermocouple pocket. The rest of the apparatus has already been described in Ch. I.

The method used here was also the same as that given by Ref.59. This work on S.S.Tube with water as the feed liquid indicated that satisfactory results could be obtained provided care was taken to ensure the proper insulation of the thermocouples. The abnormally high or even negative values for the film coeffs. reported in the above reference may have been due to faulty installation of the thermocouples. In the present investigations also similar abnormal results were obtained both with the glass-tube and the S.S.Tube evaporators when this work was first begun, and some 150 test data had to be rejected because the thermocouple indications were unreliable. It was found that in experiments under practically the same conditions, the deflections obtained became less and less in course of time, giving smaller Δt_m. A careful investigation of the thermocouples revealed that the fine coating of insulation of the inlet and outlet thermocouples gradually deteriorated, short-circuiting the wires at a point higher than the soldered tip. The thermocouples recoreded tempe-

ratures corresponding to these contact points - which were cooler - rather than to the soldered tip.

In all subsequent work, therefore, the wires were insulated by enclosing each one in a tube of insulating material for a considerable length from the soldered tip upwards. The thermocouples then gave consistent results for an indefinite period. They were calibrated from time to time to keep a check on their performance. During subsequent calibrations no material change was found.

Having made thorough investigations on the thermocouples and having obtained fairly satisfactory results with the S.S.Tube on water, more intensive work was done on a copper tube evaporator using water, 95.6 % [illegible]. ethyl alcohol, and nitration quality toluence as the feed liquids, both under natural and forced circulation. The work on the forced-circulation evaporator will be described in Chapter III.

Basis of Determination of the Liquid Film Heat Transfer Coefficients.

Hot liquids at high velocities have been previously used as heat transfer fluids by several workers. For example, Rhodes and Bridges[5] used hot mercury, circulating at high velocities through an 0.25 in. o.d. steel tube,

for studying heat transfer to liquids boiling on this tube. McMillen and Larson [Trans.Am.Inst.Chem.Engrs., 40, 177,(1944)] used a liquid heating agent flowing at high velocity and constant average temperature through the inner pipe of a double-pipe heat exchanger because this method enables the film coeff. of the heating agent to be maintained at a high constant value. Foust and Christian [Trans.Am.Inst.Chem.Engrs., 36, 541-554,(1940)] also used this method.

In the case of a vertical tube evaporator, if hot liquid is flowing through the annular space between the evaporator tube and the outer jacket and colder fluid through the evaporator tube, then,

$$U = \frac{Q}{A \cdot \Delta t_m} \quad \ldots \quad \ldots \quad \ldots \quad (2.1)$$

The overall heat transfer coeff., U, is made up of three individul coeffs. the relation among which is given by

$$\frac{1}{U} = \frac{1}{h_h} + \frac{1}{h_w} + \frac{1}{h} \quad \ldots \quad \ldots \quad \ldots (2.11)$$

Each of these terms is a resistance term, so that, the over-all resistance is made up of the resistances of the heating water film, of the tube wall, and of the liquid film inside the tube. Now "h", the film coeff. for the liquid inside the tube, can be determined from the Dittus-Boelter Equation:

$$h = 0.0225 \frac{k}{D} \cdot \left(\frac{Dv\rho}{\mu}\right)^{0.8} \left(\frac{C\mu}{k}\right)^{0.4} \quad \ldots \quad \ldots \quad (2.12)$$

with a reasonable degree of accuracy. In this equation, D, ρ and C are either constant or very nearly so, and even k varies only slightly with temperature, provided the average temperature of the liquid does not change very widely from test to test. The above equation may, therefore, be written as

$$h = K \frac{(V)^{0.8}}{(\mu)^{0.4}} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (2.13)$$

where K is roughly constant.

If, therefore, $\frac{1}{U}$ is plotted against $\frac{(\mu)^{0.4}}{(V)^{0.8}}$,

the points should lie on or about a straight line, and, if this straight line is produced back to intersect the axis for $\frac{1}{U}$, the value of the latter when

$$\frac{(\mu)^{0.4}}{(V)^{0.8}} = 0 \quad , \quad \text{i.e.,}$$

when the velocity of the feed liquid is so high as to make the resistance of the inner liquid film negligible, can be determined. The effect of using the external dia. of the tube for evaluating U would be to lower the overall coeffs. and that of using the inner dia. would be to increase the overall coeffs. slightly. In the present work, therefore, the area of the tube based on the average of

the internal and external diameters has been consistently used.

Hence, when the feed liquid velocity is infinitely high,

$$\frac{1}{U} = \frac{1}{h_h} + \frac{1}{h_w} \qquad \ldots \quad \ldots \quad \ldots \quad (2.14)$$

where the term on the right-hand side is the combined resistance of the heating fluid film and the tube wall. This term will also include the effect of any scales on either side of the tube wall. The values of the various liquid properties are evaluated at its average temperature inside the evaporator tube.

This derivation also assumes the constancy of resistance for both the retaining wall and the inner liquid film. Such an assumption is obviously not rigorous but the error introduced thereby is not serious compared to the total magnitude of the resistances involved. This is indicated by the satisfactory approach of the experimental values to a straight line when a plot is made as suggested above.

.....

PART I.

The Stainless-Steel tube Evaporator.

This was used as a Natural-Circulation, Vertical, Evaporator with water as the feed liquid. First of all, the resistance term, $\left(\frac{1}{h_h} + \frac{1}{h_w}\right)$, was determined. For this purpose the form of the apparatus shown in Fig.2.2 was used so that temperatures of heating water and feed water could be read, both at inlet and outlet, by means of thermometers, and the feed liquid could be weighed by means of a weighing tank.

Experimental Procedure for the Establishment of $\left(\frac{1}{h_h} + \frac{1}{h_w}\right)$:-

Heating water at 80°C was pumped through the jacket, co-current with the feed water, at the rate of about 20 gallons/minute. The feed water was admitted from a tap. Some of it was allowed to bye-pass so that its temperature at inlet could be measured. The plant was allowed to run for some minutes for stady conditons to be attained, the feed going to waste during this period. When the thermometer readings became steady the feed at outlet was switched to a weighed tank and the following observations made at one minute intervals:-

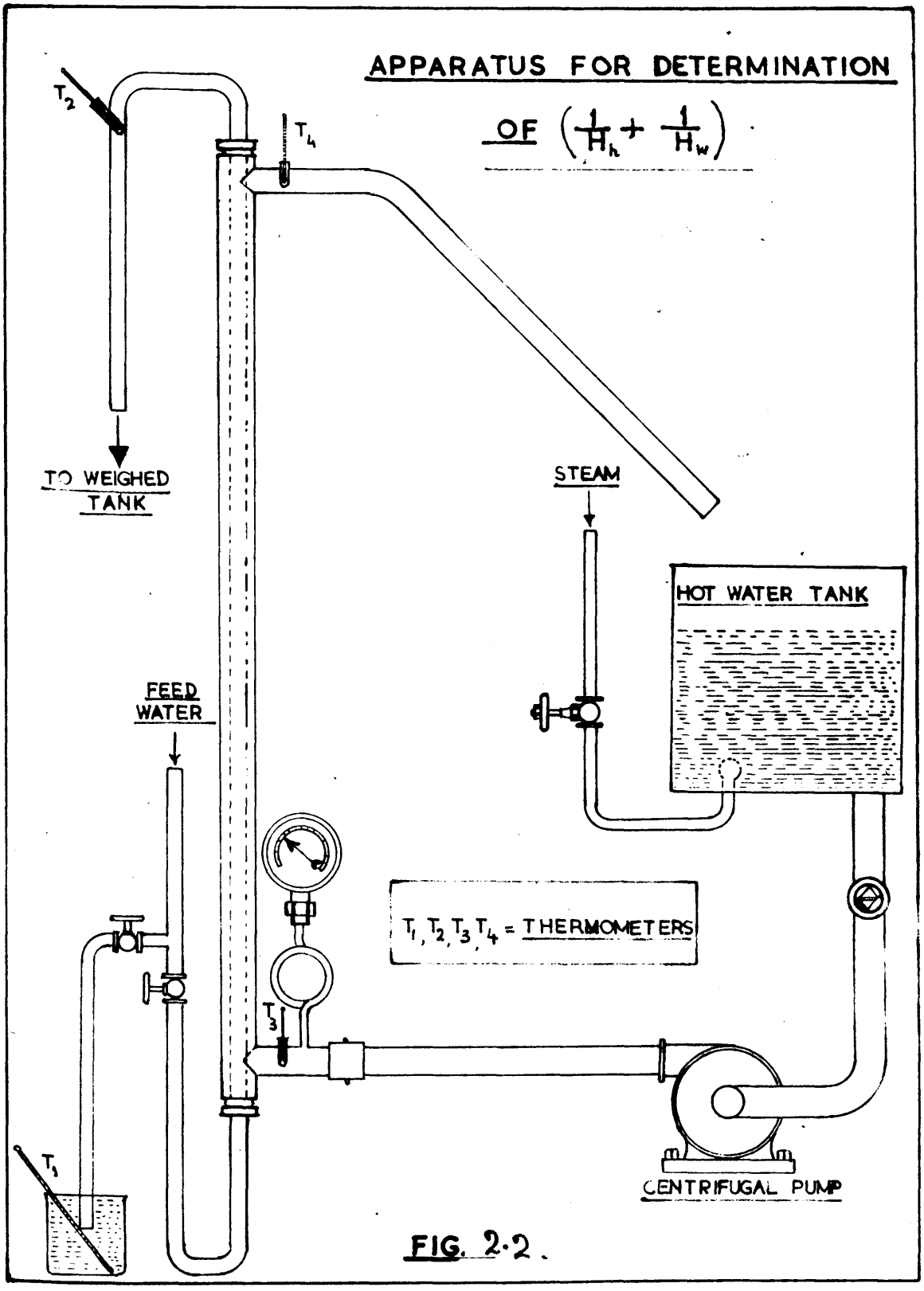

APPARATUS FOR DETERMINATION
OF $\left(\frac{1}{H_h} + \frac{1}{H_w}\right)$
T_2
T_4
TO WEIGHED TANK
STEAM
HOT WATER TANK
FEED WATER
T_1, T_2, T_3, T_4 = THERMOMETERS
T_3
T_1
CENTRIFUGAL PUMP

FIG. 2·2.

(1) Inlet temp. of heating water

(2) Outlet ,, ,, ,, ,,

(3) Inlet ,, ,, feed ,,

(4) Outlet ,, ,, ,, ,,

The time for which the feed collected in the weighed tank was recorded by a stop-clock. The experiment was concluded after 10 minutes.

Calculations:-

The Heat Load, q, was calculated directly from feed rate and temperature rise. The log mean temp. drop, Δt_m, was calculated in the normal way. It may be noted that the flow of both water streams was in the same direction. The Heating Area of the tube was calculated on the basis of the average of the inner and outer diameters and is equal to 1.44 sq.ft. V, ρ, & μ were evaluated on the basis of the mean temp. of the liquid in the tube.

The results are given in Table 2.1. A plot of $\frac{1}{U}$ vs. $\frac{(\mu)^{0.4}}{(V)^{0.8}}$ is shown in Fig. 2.22. The points lie on a straight line with an intercept on the $\frac{1}{U}$ axis of 0.0013 $\frac{(hr)(sq.ft.)(^{o}F)}{B.\ Th.\ U.}$.

Determination of Coefficients for water:-

Having determined

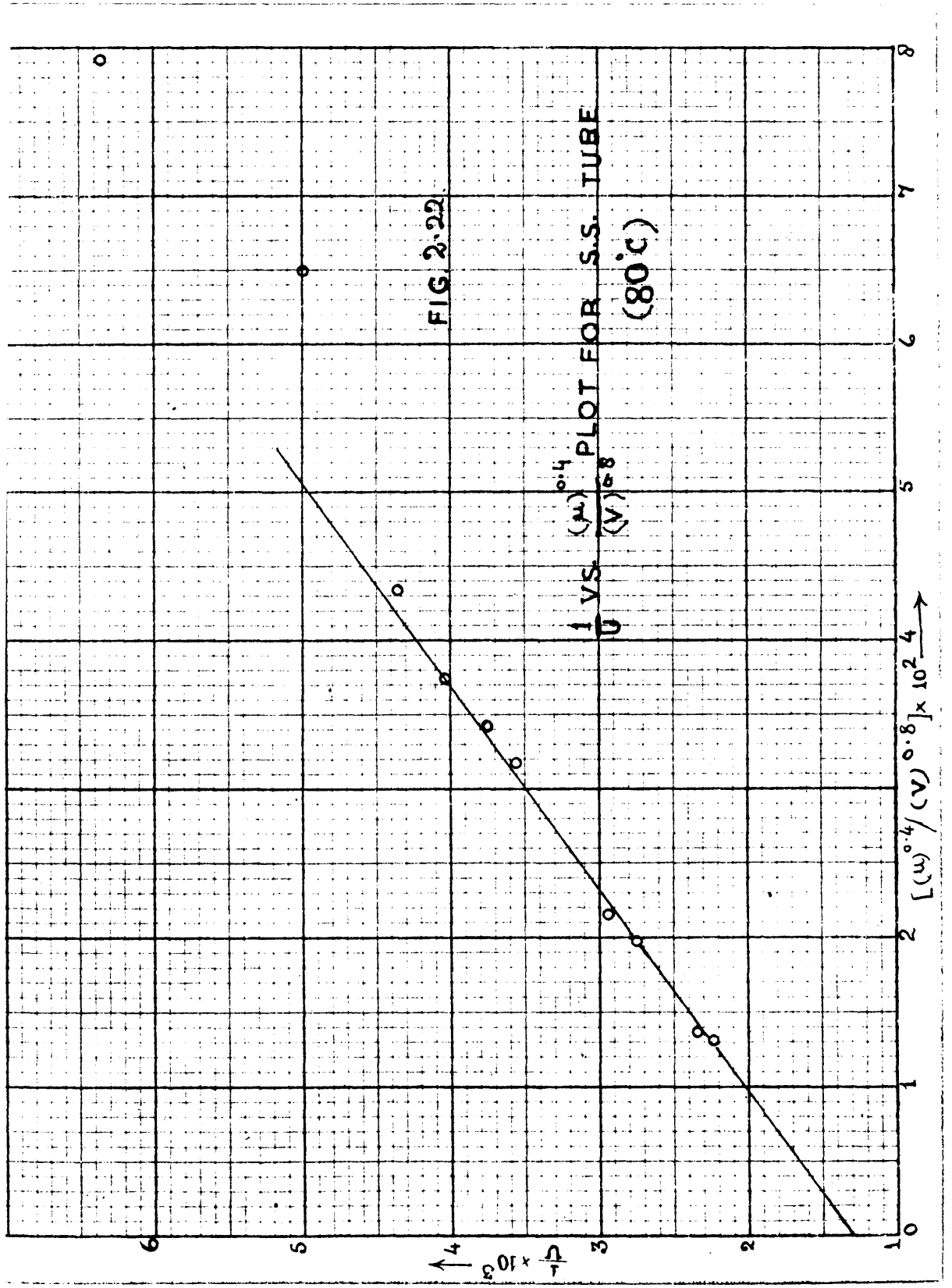


FIG. 2.22
$\frac{1}{U}$ VS. $\frac{(\mu)^{0.4}}{(V)^{0.8}}$ PLOT FOR S.S. TUBE (80°C)
$\frac{1}{U} \times 10^3$
$[(\mu)^{0.4}/(V)^{0.8}] \times 10^2$
0
1
2
3
4
5
6
7
8

the resistance term, the apparatus was assembled to its normal form shown in Fig. 2.1. Hot water was circulated at 80°C. The experimental procedure and calculations were the same as described in detail in CHAPTER I. The overall coeffs., U and U_B, were directly obtained by calculations. The coresponding film coeffs., h and h_B, for the entire tube and for the boiling section, respectively, were then evaluated from the following relationships:-

$$\frac{1}{h} = \frac{1}{U} - \left[\frac{1}{h_h} + \frac{1}{h_w}\right] \quad \ldots \quad \ldots \quad \ldots \quad (2.15)$$

$$\frac{1}{h_B} = \frac{1}{U_B} - \left[\frac{1}{h_h} + \frac{1}{h_w}\right] \quad \ldots \quad \ldots \quad \ldots \quad (2.16)$$

where $\left[\frac{1}{h_h} + \frac{1}{h_w}\right] = 0.0013 \ \frac{(hr)(sq.ft.)(^{\circ}F)}{B.\ Th.U.}$.

Results:-

These are given in Table 2.2. The values of h_B are of the same order as those obtained by Stroebe, Baker and Badger[45] for the boiling film coefficient for water in an LTV evaporator under similar conditions of boiling point and mean temperature drops across the liquid film in the boiling section. The values of U and of U_B calculated on the basis of a boiling section show a relative constancy with feed rate, as noted previously (Ref. 59). The value of h_B begins to vary rather widely as liquid

rates increase. This may be due to a breaking down in the division of the tube into boiling and non-boiling sections, or to inaccuracies in measurement.

Ideally the value of the outer film coefficient and of the conductivity of the tube wall should be so high that the resistance to heat flow is concentrated in the boiling film. This is not the case here as the value of the combined coefficient is 769.2 (= $\frac{1}{0.0013}$) B.Th.U./hr/sq.ft./°F, and, as a result, calculation grows increasingly difficult as apparent overall coefficients rise. If the overall coefficient reaches 769.2 B.Th.U./hr/sq.ft./°F then, clearly, there would be no resistance to heat flow in the boiling film at all.

For this reason it was decided to alter the stainless-steel wall to a thinner one of copper.

PART II.

COPPER-TUBE, VERTICAL, EVAPORATOR.

The copper-tube evaporator was 10 ft. long x $\frac{19}{32}$ in. o.d. x $\frac{15}{32}$ in. i.d., heated for 9 ft. 2 in. of its length. A screw-thread was cut on top end of this tube which was screwed directly into the brass gland-piece with the side-tube for connecting the top of the

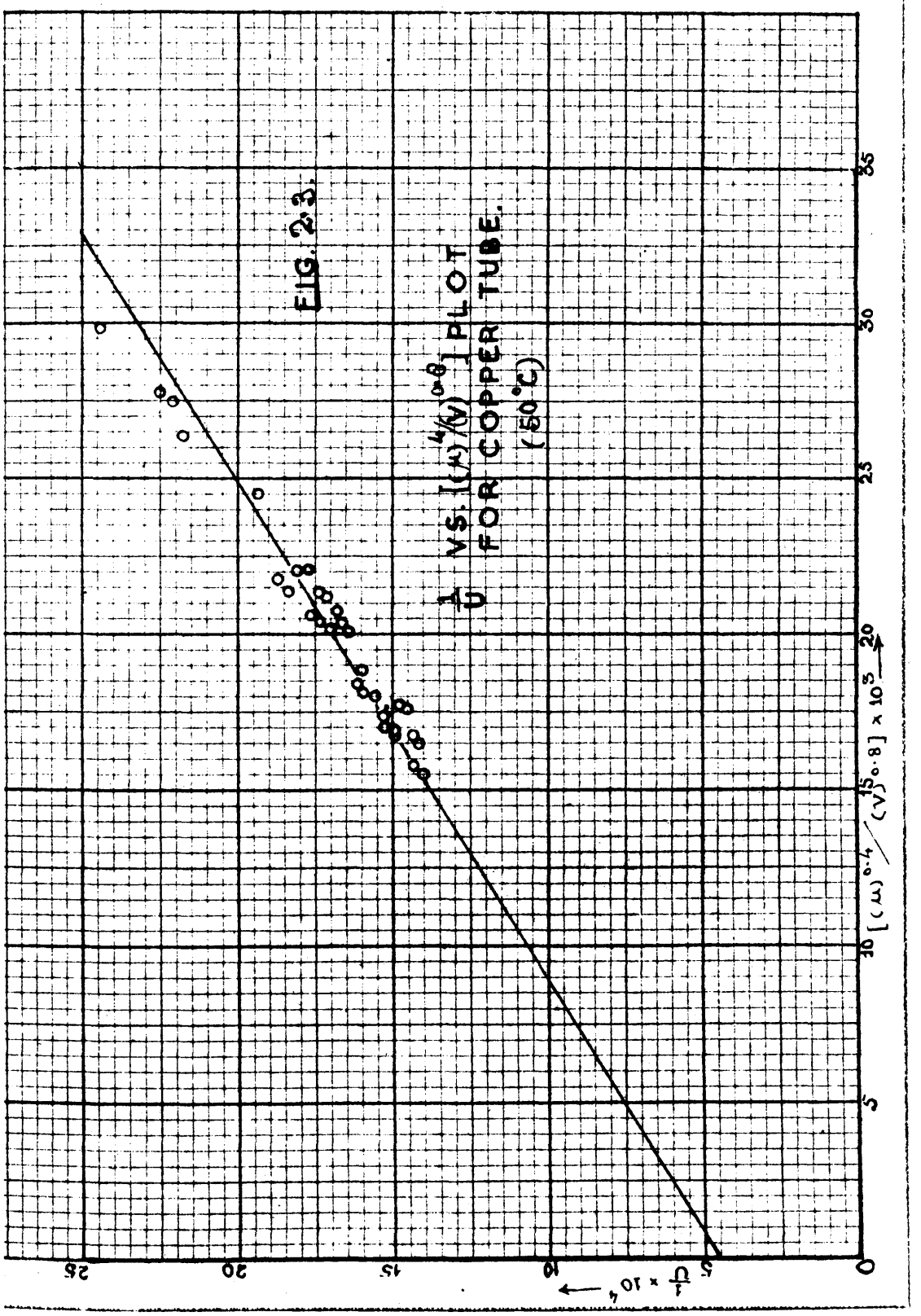


FIG. 23.
$\frac{1}{U}$ VS. $[(\mu)^{0.4}/(V)^{0.8}]$ PLOT
FOR COPPER TUBE.
(50°C)
$\frac{1}{U} \times 10^4$
$[(\mu)^{0.4}/(V)^{0.8}] \times 10^5$
0
5
10
15
20
25
30
35

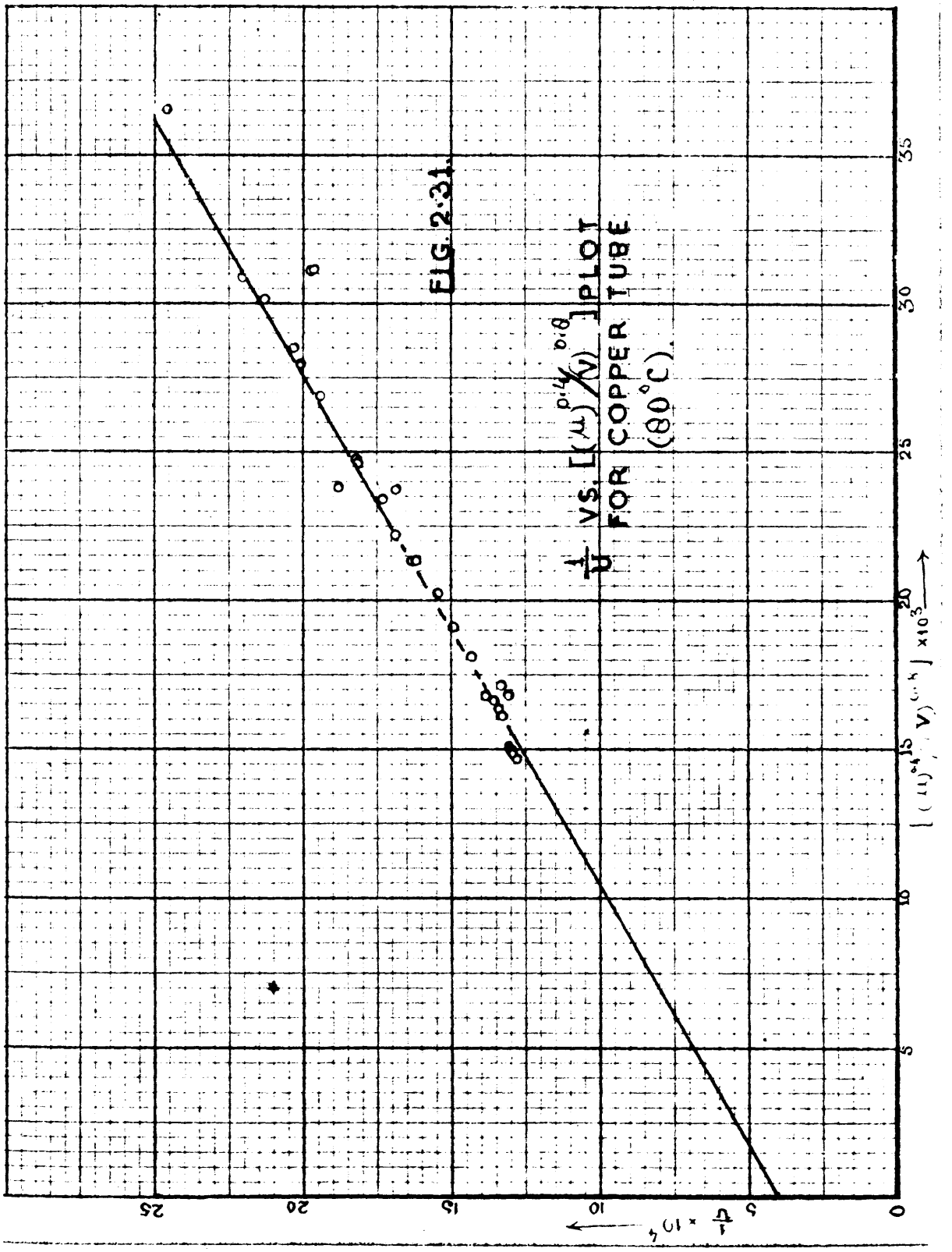


FIG. 2.31.
$\frac{1}{U}$ VS. $[(\mu)^{0.4}/(V)^{0.8}]$ PLOT
FOR COPPER TUBE
(80°C).
$\frac{1}{U} \times 10^4$
$[(\mu)^{0.4}/(V)^{0.8}] \times 10^3$
0
5
10
15
20
25
30
35

evaporator tube to the separator. This copper tube could be held inside the iron jacket, used with the S.S. tube evaporator, by means of the same stuffing boxes and gland-nuts as used before, so that no other alteration in the set-up was necessary. (Fig.2.1).

The resistance term $(\frac{1}{h_h} + \frac{1}{h_w})$, was first determined both at 50°C and at 80°C. The apparatus was modified to the form of Fig. 2.2. This determination was made as in the case of the S.S.tube. The results are given in Tables 2.3 and 2.31, and a plot of $\frac{1}{U}$ vs. $\frac{(\mu)^{0.4}}{(V)^{0.8}}$ for 50°C and 80°C is shown in Figs. 2.3 and 2.31, respectively.

The values obtained by extrapolation are as follows:-

Combined Resistance, $(\frac{1}{h_h} + \frac{1}{h_w})$, at 50°C = 0.00045 $\left.\right\}$ $\frac{(hr)(sq.ft)(^oF)}{B.Th.U.}$

" " " " " 80°C = 0.00040 $\left.\right\}$

Determination of Boiling Film Coeffs:-

The apparatus was now assembled to the form of Fig.2.1. Experimental procedure and calculations were the same as already detailed in CH.I., and in PART I of this chapter.

The following liquids were used:-

(1)water; (2)95.6% Et.OH; and (3)Nitration Quality Toluene. The results are given in Tables 2.4, 2.5 and 2.6, respectively.

TABLE. 2.1

STAINLESS STEEL TUBE EVAPORATOR.

Determination of $(1/h_h + 1/h_w)$.

Heating Water at 80°C.

Heating Area of Tube = 1.44 sq.ft.

Test No.	Feed Rate lbs/hr	Feed Water Temp. (°F) In	Feed Water Temp. (°F) Out	Heating Water Temp. (°F) In	Heating Water Temp. (°F) Out	Δt_m °F	Velocity (V) ft/sec.	q	U	$\frac{1}{U} \times 10^6$	$\mu \times 10^4$	$\frac{DV\rho}{\mu}$	$\frac{V^{0.8}}{\mu^{0.4}}$	$\frac{\mu^{0.4}}{V^{0.8}} \times 10^5$
1.	153	56.39	150.49	178.84	178.03	63.55	0.500	14440	157.8	6336	4.434	3514	12.60	7937
2.	198	56.30	147.52	175.69	175.32	62.81	0.647	18115	200.4	4990	4.514	4466	15.38	6502
3.	351	53.42	127.94	176.80	175.60	79.68	1.148	26160	228.0	4386	5.098	7011	23.16	4318
4.	404	55.63	126.32	176.97	175.86	80.27	1.319	28530	246.8	4052	5.081	8087	25.93	3856
5.	468	53.78	121.46	174.88	173.32	81.80	1.529	31660	268.8	3720	5.279	9036	28.75	3478
6.	513	53.06	118.90	175.42	173.83	83.75	1.677	33780	280.0	3571	5.381	10160	31.27	3198
7.	870	49.01	102.74	176.71	172.22	95.85	2.843	46740	338.6	2964	6.091	14500	44.59	2252
8.	1008	51.98	100.24	174.20	170.25	93.87	3.294	48570	359.3	2784	6.075	16890	50.20	1992
9.	1230	49.51	93.92	175.73	169.34	98.72	4.020	54630	384.0	2604	6.437	19450	57.51	1739
10.	1326	49.10	92.98	176.72	170.06	100.20	4.330	58190	40216	2492	6.485	20820	60.91	1642

(TABLE. 2.1)

T A B L E .2.2.

WATER IN STAINLESS STEEL TUBE EVAPORATOR.

Heating Water at 80°C. Total Heat Transfer Area = 1.44 sq.ft.

Test No.	Feed Rate lbs/hr	Evaporation lbs/hr	Initial Feed Temp. °F.	Tube Top Temp. °F.	Max. Liquid Temp. °F.	q	Δt_m °F	U	q_B	Δt_B °F	Boiling Area sq.ft.	U_B	h_B
1.	21.39	12.12	57.2	153.8	161.8	14260	21.95	451	12022	16.92	1.298	548	1905
2.	25.84	11.63	75.2	151.1	160.1	13682	23.70	401	11470	19.27	1.296	460	1144
3.	33.19	11.33	59.0	153.8	162.0	14548	21.52	470	11128	16.92	1.218	540	1812
4.	33.98	11.18	56.3	152.1	161.4	14517	23.20	435	10965	18.78	1.218	480	1277
5.	39.32	10.36	65.3	154.4	163.2	13924	22.10	440	10074	16.16	1.192	523	1634
6.	39.69	10.39	56.3	154.7	162.1	14337	21.17	471	10142	16.54	1.192	515	1559
7.	44.89	10.49	57.2	153.1	162.1	14866	22.30	463	10160	15.77	1.165	554	1980
8.	45.25	10.00	51.8	153.7	163.4	14670	21.72	470	9620	16.20	1.165	510	1514
9.	47.71	10.46	66.2	154.8	164.1	14750	21.84	470	10080	15.55	1.140	569	2188
10.	51.01	9.88	54.0	153.5	162.1	15020	23.40	446	9510	16.35	1.139	511	1522
11.	54.71	9.71	54.5	154.7	163.2	15250	22.10	465	9300	15.42	1.087	555	1993
12.	65.70	9.55	55.4	153.9	162.1	16090	25.70	435	9080	16.36	1.060	524	1644
13.	68.90	9.75	58.1	156.0	164.1	16540	23.48	489	9240	14.63	1.034	610	2950
14.	86.63	8.83	52.7	155.8	164.3	17810	26.53	467	8145	15.18	0.903	595	2627
15.	100.15	8.75	54.5	156.2	164.1	19360	26.93	500	8380	14.91	0.878	640	3817

T A B L E . 2.3.

(TABLE. 2.3)

COPPER TUBE EVAPORATOR.

Determination of ($1/h_h + 1/h_w$) at 50°C ;

Heating Area of Tube, based on average of internal and external diameters = 1.275 sq. ft.

Test No.	Feed Rate lbs/hr	Feed Temp. °F In	Feed Temp. °F Out	Heating Water Temp. (°F). In	Heating Water Temp. (°F). Out	Δt_m °F	q	U	$\frac{1}{U} \times 10^6$	V ft/sec	$\mu \times 10^7$	$\frac{DV\rho}{\mu}$	$\frac{V^{0.8}}{\mu^{0.4}}$	$\frac{\mu^{0.4}}{V^{0.8}} \times 10^5$	Test No.
SERIES : 1.															**Series: 1.**
1.	554.5	48.0	91.8	122.0	118.6	46.5	24270	409.4	2443	2.062	6583	7630	33.42	2992	1.
2.	607.4	49.0	91.9	122.0	118.4	45.9	26040	445.2	2246	2.259	6582	8350	35.96	2781	2.
3.	618.7	48.0	91.0	121.7	117.8	46.0	26600	453.5	2205	2.300	6615	8460	36.41	2745	3.
4.	667.5	48.2	91.2	122.0	118.2	46.6	28700	483.4	2079	2.485	6996	8645	37.88	2640	4.
5.	722.0	48.2	90.8	122.0	117.9	46.6	30700	517.0	1934	2.686	6617	9880	41.21	2427	5.
6.	811.5	47.7	89.6	122.0	117.5	47.4	34000	563.0	1776	3.019	6695	10900	45.04	2220	6.
7.	818.0	47.8	88.6	122.0	117.0	47.7	33400	550.0	1818	3.047	6750	10994	45.23	2211	7.
8.	853.0	47.6	88.8	122.0	117.0	47.9	35150	576.0	1736	3.173	6740	11460	46.74	2140	8.
9.	860.5	48.0	89.1	122.0	117.3	47.6	35,380	584.0	1712	3.200	6700	11620	47.17	2120	9.
10.	888.5	47.3	88.5	122.0	117.2	48.1	36600	598.0	1672	3.305	6763	11890	48.22	2074	10.
11.	905.0	48.2	88.5	122.0	117.1	47.7	36480	601.0	1664	3.365	6732	12160	49.01	2040	11.
12.	924.2	47.8	87.9	122.0	116.4	47.8	37060	609.2	1641	3.440	6740	12440	49.86	2006	12.
13.	975.0	48.0	87.8	122.0	117.8	48.7	38700	624.2	1602	3.625	6765	13040	53.13	1882	13.
14.	1092.0	48.7	87.3	122.0	116.6	48.0	42140	689.0	1451	4.060	6750	14640	56.90	1758	14.
15.	1094.0	47.1	86.0	122.0	116.4	49.4	42540	676.0	1479	4.067	6885	14360	56.53	1769	15.
SERIES : 2.															**Series :2.**
1.	832.0	48.7	88.3	122.1	118.1	48.37	32930	534.5	1871	3.095	6708	11230	45.91	2179	1.
2.	848.0	48.7	88.2	122.0	118.0	48.35	33480	544.5	1836	3.154	6715	11425	46.59	2147	2.
3.	895.0	47.8	87.3	121.9	117.6	49.00	35350	566.0	1767	3.330	6792	11930	48.43	2065	3.
4.	900.0	48.8	88.1	122.1	117.6	48.17	35370	576.0	1736	3.350	6710	12160	48.90	2045	4.
5.	921.0	47.6	87.4	122.1	117.5	49.00	36650	587.0	1704	3.427	6802	12270	49.53	2019	5.
6.	1032	48.7	86.0	122.0	117.0	49.15	38500	615.0	1626	3.838	6812	13700	54.20	1845	6.
7.	1053	47.8	85.7	122.0	116.8	49.92	39900	627.0	1595	3.915	6868	13880	54.88	1822	7.
8.	1072	48.2	85.9	122.0	117.1	49.50	40400	640.0	1562	3.985	6841	14190	55.74	1794	8.
9.	1127	46.8	84.5	122.0	116.9	50.78	42500	656.5	1523	4.192	6975	14630	57.61	1735	9.
10.	1151	47.5	84.3	122.0	116.6	50.47	42360	658.0	1520	4.283	6950	15010	58.68	1704	10.
11.	1160	47.8	84.0	122.0	116.7	50.13	42800	670.0	1493	4.315	6919	15190	59.14	1691	11.
12.	1176	47.5	84.2	122.0	116.6	50.52	43170	670.0	1493	4.374	6951	15310	59.69	1675	12.
13.	1263	49.6	84.3	121.9	116.0	49.28	43800	698.0	1433	4.700	6850	16700	63.59	1573	13.
14.	1293	48.6	83.7	122.0	116.2	50.20	45370	709.5	1409	4.812	6912	16950	64.56	1549	14.
15.	1298	48.7	83.6	122.5	116.1	50.35	45290	705.5	1417	4.830	6912	17000	64.76	1545	15.

TABLE. 2.31.

COPPER TUBE EVAPORATOR.

Determination of ($1/h_h + 1/h_w$) at 80°C.

(TABLE. 2.31.)

Heating Area of Tube = 1.275 sq.ft.

Test No.	Feed Rate lbs/hr	Feed Temp. (°F) In	Feed Temp. (°F) Out	Heating Water Temp. (°F). In	Heating Water Temp. (°F). Out	Δt_m	q	U	$\frac{1}{U}\times10^6$	V ft/sec	$\mu \times 10^7$	$\frac{DV\rho}{\mu}$	$\frac{V^{0.8}}{\mu^{0.4}}$	$\frac{\mu^{0.4}}{V^{0.8}} \times 10^5$	Test No.
SERIES : 1.															SERIES : 1.
1.	373.0	46.4	141.5	176.0	171.6	68.20	35460	408.0	2451	1.388	4915	6863	27.37	3654	1.
2.	450.5	55.6	140.2	176.0	171.0	65.80	38110	454.0	2203	1.678	4700	8656	32.41	3085	2.
3.	452.2	48.2	142.6	175.9	170.5	65.66	42700	510.0	1961	1.682	4850	8442	32.02	3123	3.
4.	452.5	47.2	142.4	176.0	170.6	66.52	43100	508.0	1969	1.683	4875	8400	32.05	3120	4.
5.	481.0	46.4	136.4	175.9	170.5	72.20	43290	470.0	2128	1.788	5050	8623	33.16	3016	5.
6.	515.0	47.8	135.3	175.9	170.2	71.70	45050	493.0	2028	1.916	5040	9250	35.07	2851	6.
7.	539.0	48.2	135.8	176.0	169.8	72.60	46140	498.5	2006	2.005	5075	9620	36.27	2757	7.
8.	560.0	46.4	133.5	176.3	170.3	74.40	48780	514.0	1946	2.083	5135	9870	37.22	2687	8.
9.	605.0	47.5	131.0	175.7	169.6	74.80	50500	530.0	1887	2.250	5280	10367	41.95	2384	9.
10.	624.0	48.6	131.5	176.0	169.2	73.58	51720	551.5	1813	2.320	5135	11000	40.57	2465	10.
11.	625.3	46.4	130.7	175.9	169.2	76.00	52700	544.0	1838	2.325	5217	10766	40.39	2476	11.
12.	653.0	47.3	132.5	175.9	169.1	73.30	55630	596.0	1678	2.430	5135	11520	42.10	2375	12.
13.	671.5	46.4	129.8	176.3	169.0	75.86	55940	578.5	1729	2.497	5250	11560	42.64	2345	13.
14.	713.0	48.9	128.7	176.2	168.7	75.50	56900	591.5	1691	2.653	5208	12400	44.91	2226	14.
15.	738.0	51.7	130.1	176.0	168.4	73.20	57850	620.0	1613	2.750	5080	13164	46.68	2142	15.
16.	757.0	48.2	127.1	176.0	168.0	76.35	59700	613.0	1631	2.815	5280	12980	46.84	2135	16.
17.	806.0	47.2	126.2	176.0	167.9	77.30	63650	646.0	1548	3.000	5240	13935	49.43	2023	17.
18.	876.6	48.2	124.6	175.7	168.3	78.30	67000	671.0	1490	3.260	5358	14820	52.36	1910	18.
19.	928.0	50.8	125.2	176.3	168.2	77.10	69000	702.0	1425	3.452	5255	15920	55.24	1811	19.
20.	1005.0	48.2	123.0	176.1	167.1	78.70	75200	750.0	1333	3.740	5410	16840	58.21	1718	20.
21.	1050.0	46.8	120.5	175.3	165.5	79.60	77400	763.0	1311	3.905	5535	17180	59.60	1678	21.
SERIES : 2.															SERIES: 2.
1.	1048	47.8	119.7	176.0	167.0	81.20	75350	727.5	1375	3.896	5527	17180	59.64	1677	1.
2.	1054	47.5	120.0	176.1	167.4	81.35	76400	737.0	1357	3.920	5533	17260	59.91	1669	2.
3.	1084	47.1	119.2	176.0	167.6	82.20	78100	745.0	1342	4.030	5568	17640	61.10	1637	3.
4.	1104	46.6	118.4	176.0	167.0	82.50	79250	753.5	1329	4.105	5610	17820	61.80	1618	4.
5.	1134	47.7	118.3	176.0	167.2	82.35	80000	763.0	1311	4.220	5580	18370	63.33	1579	5.
6.	1203	47.4	116.0	176.1	166.8	83.80	82500	772.0	1295	4.470	5667	19220	65.90	1517	6.
7.	1204	48.2	116.6	176.1	166.6	82.90	82300	779.0	1284	4.474	5616	19400	66.19	1511	7.
8.	1224	48.2	115.7	176.2	166.2	83.30	82600	778.0	1285	4.550	5650	19620	66.93	1494	8.
9.	1236	47.5	115.1	176.1	166.8	84.45	83500	776.0	1289	4.596	5695	19660	67.25	1487	9.
10.	1252	47.7	115.2	176.4	166.6	84.20	84500	787.0	1271	4.656	5690	19910	67.98	1471	10.

T A B L E. 2.4.

COPPER TUBE EVAPORATOR.
DETERMINATION OF COEFFICIENTS FOR WATER.

(Table. 2.4)

Heating Water at 80°F.

Total Heat Transfer Area of Tube = 1.275 sq.ft.

Test No.	Feed Rate lbs/hr	Evaporation. lbs/hr	Feed Temp; °F	Tube-Top Temp. °F	Max. Temp. of Liquid °F.	q B.Th.U/hr.	Δt_m °F.	U	q_{NB}	Δt_{NB} °F	U_{NB}	q_B	Δt_B °F	Boiling Area Sq.Ft.	U_B	h_B	h
1.	20.40	15.94	60.8	160.7	168.8	18020	14.14	1000	2205	59.84	159	15815	10.64	1.0430	1426	3215	1670
2.	31.73	14.27	54.0	158.5	169.4	17635	16.80	823	3660	35.80	368	13975	11.20	0.9970	1252	2510	1223
3.	38.49	13.39	66.2	159.9	171.0	17025	13.81	968	4035	27.54	528	12990	10.00	0.9970	1330	2840	1580
4.	40.58	13.33	52.7	158.3	169.0	17665	17.54	791	4725	40.65	418	12940	11.10	0.9970	1170	2200	1156
5.	43.48	12.74	51.8	159.1	169.7	17445	17.34	790	5122	41.40	445	12325	10.65	0.9970	1161	2170	1155
6.	53.38	12.64	54.5	159.1	169.7	18260	16.32	878	6310	37.10	612	11950	10.55	0.9970	1137	2085	1355
7.	53.58	12.38	54.3	160.2	170.0	18090	18.00	788	6200	46.80	477	11890	9.98	0.9970	1196	2290	1150
8.	55.09	12.12	52.7	160.2	167.6	18070	19.45	729	6360	51.64	443	11710	10.51	0.9970	1118	2020	1030
9.	56.43	13.13	44.8	159.5	168.2	19640	19.15	805	6970	47.90	626	12670	11.11	1.0425	1095	1930	1186
10.	57.28	12.88	45.5	159.1	170.1	19850	18.90	824	7130	54.80	510	12720	9.80	1.0200	1272	2580	1269
11.	57.72	11.48	46.8	159.5	170.2	18015	17.30	818	7125	42.50	604	10890	10.30	0.9970	1062	1845	1217
12.	58.27	12.37	48.2	158.4	168.3	18840	20.80	710	7000	43.75	576	11840	11.41	0.9970	1040	1780	999
13.	61.03	12.13	48.4	160.4	166.5	19020	22.85	657	7205	45.38	457	11815	12.87	0.9270	991	1640	892
14.	61.10	11.89	54.5	158.9	168.8	18315	19.12	752	6980	42.60	505	113355	10.86	0.9505	1099	1960	1075
15.	61.84	12.12	48.4	159.5	169.7	19030	16.82	885	7500	41.78	596	11530	9.90	0.9737	1197	2290	1370
16.	62.54	11.77	56.0	159.1	169.6	18300	19.20	748	7100	51.48	496	11200	10.25	0.9970	1096	1950	1063
17.	63.45	12.62	51.8	159.1	168.3	19470	18.42	829	7390	41.40	593	12080	10.94	0.9738	1134	2070	1240
18.	63.88	11.78	51.3	159.2	169.5	18715	18.55	791	7550	41.70	558	11165	10.38	0.9505	1132	2070	1156
19.	64.88	11.68	56.8	158.9	168.6	18345	20.50	702	7250	46.66	419	11095	10.74	0.9040	1143	2110	976
20.	65.76	11.56	46.4	158.5	168.7	18970	20.77	716	8030	48.00	516	10940	10.04	0.9505	1147	2120	1003
21.	71.02	11.07	51.8	159.2	170.6	18740	19.10	770	8440	38.58	572	10300	10.58	0.8925	1092	1940	1113
22.	71.69	11.29	51.8	159.1	169.2	19020	19.80	754	8420	41.18	535	10600	10.46	0.8925	1135	2075	1080
23.	72.17	12.37	46.6	159.5	168.3	20550	18.82	857	8780	43.75	619	11770	10.93	0.9505	1134	2070	1305
24.	75.32	11.15	45.5	159.5	168.7	19770	24.60	631	9190	47.77	415	10580	11.03	0.8110	1182	2235	844
25.	77.66	11.76	47.1	158.7	168.6	20470	22.60	710	9430	43.10	572	11040	12.60	0.8925	982	1620	999
26.	77.71	11.81	47.3	158.4	168.3	20485	20.94	768	9400	45.78	554	11085	11.10	0.9040	1105	1970	1107
27.	77.80	11.50	46.4	159.7	170.0	20350	19.48	820	9610	41.43	625	10740	9.90	0.9040	1200	2310	1220
28.	78.10	11.45	50.0	159.9	170.1	20070	19.14	823	9370	43.20	585	10700	9.65	0.9040	1227	2410	1217
29.	79.93	11.23	49.3	159.5	169.7	20060	20.58	765	9630	42.48	543	10430	9.98	0.8575	1220	2380	1102
30.	86.66	11.26	47.3	159.8	169.8	21040	20.26	815	10610	42.22	603	10430	9.64	0.8575	1262	2550	1210
31.	87.60	11.10	45.5	160.2	170.6	21170	23.52	706	10950	47.67	472	10220	9.56	0.7880	1358	2970	984
32.	87.91	11.21	49.3	160.2	170.4	20995	20.08	820	10650	42.00	608	10345	9.53	0.8575	1267	2570	1220
33.	88.01	10.96	52.7	160.2	169.8	20450	23.95	670	10300	46.90	452	10150	9.50	0.7880	1358	2970	915
34.	88.03	11.08	46.4	160.2	170.6	21130	19.88	834	10930	39.83	623	10200	9.23	0.8346	1324	2815	1253
35.	88.12	10.96	46.4	160.2	169.7	21030	22.30	740	10860	44.30	529	10170	9.31	0.8110	1348	2930	1051
36.	88.88	10.90	55.4	158.7	169.7	20115	23.44	674	10160	45.98	455	9955	10.24	0.7880	1235	2450	923
37.	90.08	11.38	46.5	160.2	170.4	21670	21.00	810	11170	40.46	595	10500	9.62	0.8110	1346	2755	1198
38.	97.62	10.62	35.5	160.0	169.0	21830	22.45	763	12050	39.15	554	9780	9.55	0.7185	1424	3310	1098
39.	112.08	10.78	46.4	159.7	168.6	23510	26.60	693	13680	42.00	562	9830	10.18	0.6955	1390	3130	959
40.	113.15	10.85	46.4	160.2	168.8	25240	28.87	686	16290	44.41	586	8950	10.28	0.6790	1505	3790	945

T A B L E . 2.5.

ETHYL ALCOHOL IN COPPER-TUBE, NATURAL-CIRCULATION, EVAPORATOR.
Heating Water at 50°C. Total Heating Area of Tube = 1.275 sq. ft.

Test No.	Feed Rate lbs/ hr.	Evapo-ration lbs/hr	Initial Feed Temp. °F.	Tube Top Temp. °F.	Max. Liquid Temp. °F	q	Δt_m °F	U	q_B	Δt_B °F	Boiling Area sq.ft.	U_B	h_B
1.	15.66	11.60	50.5	102.9	110.0	5417	18.09	234.9	4809	15.10	1.1360	280.5	321.0
2.	15.89	11.32	43.2	103.1	109.6	5374	18.66	225.9	4691	15.28	1.1128	276.3	315.6
3.	16.42	10.93	49.1	103.3	110.6	5171	17.62	230.2	4506	14.72	1.1128	275.5	314.6
4.	16.89	11.51	55.8	102.7	109.8	5356	17.81	235.7	4754	15.15	1.1360	276.5	315.9
5.	18.39	10.07	51.8	103.8	110.5	4809	17.08	221.0	4155	14.22	1.1360	257.2	290.8
6.	18.96	10.09	50.5	104.0	110.6	4903	17.41	221.1	4157	14.22	1.1012	265.8	301.8
7.	19.19	11.60	43.7	102.9	109.8	5505	18.39	234.8	4682	15.09	1.1244	276.1	315.2
8.	19.37	10.09	51.1	103.8	110.7	4906	17.05	225.7	4139	14.22	1.0896	267.5	304.1
9.	19.43	10.93	62.3	103.3	110.5	5112	17.03	235.6	4494	14.90	1.1128	271.3	309.2
10.	20.24	9.72	55.8	104.4	110.8	4730	16.55	224.2	3994	13.99	1.1128	257.0	290.6
11.	21.21	11.16	59.0	102.7	110.1	5308	16.44	253.0	4582	14.45	1.1128	285.0	326.9
12.	21.84	10.26	57.2	103.7	110.5	4983	16.98	230.3	4210	14.59	1.0896	265.0	300.8
13.	22.32	9.52	53.6	104.2	111.2	4736	16.08	231.0	3883	13.76	1.0664	265.0	300.8
14.	24.10	10.90	55.4	102.5	110.1	5321	17.02	245.4	4450	14.82	1.0425	288.1	331.0
15.	24.11	9.70	55.0	104.0	111.2	4850	16.28	233.6	3953	14.08	1.0425	269.6	306.8
16.	25.19	9.56	56.8	104.0	111.4	4793	15.78	238.4	3884	13.80	1.0425	270.1	307.4
17.	26.38	9.87	49.5	104.0	111.7	5079	16.70	238.5	3996	13.58	1.0200	288.5	331.6
18.	26.64	9.84	49.1	104.0	111.5	5080	16.28	244.8	3990	13.48	1.0200	290.3	333.8
19.	27.10	10.42	50.9	102.9	110.7	5296	17.02	244.1	4230	14.40	1.0425	281.6	322.4
20.	28.66	9.20	49.5	104.5	111.7	4887	16.09	238.2	3714	14.00	0.9970	266.4	302.7
21.	28.74	9.83	50.0	103.8	111.7	5132	16.28	247.5	3966	13.44	0.9970	296.4	342.2
22.	29.02	10.40	54.0	103.1	110.9	5299	16.63	250.0	4209	14.22	1.0425	284.0	325.6
23.	29.87	10.07	59.0	103.6	111.4	5110	15.66	256.1	4063	13.61	1.0425	286.6	328.9
24.	30.04	10.28	50.2	103.6	111.5	5361	16.20	259.5	4148	13.62	1.0200	298.9	345.3
25.	30.09	9.85	55.4	103.6	111.7	5087	16.16	247.0	3965	13.44	0.9970	296.4	342.2
26.	30.44	9.24	59.0	104.7	112.1	4799	15.85	237.5	3718	13.40	1.0200	272.4	310.5
27.	31.06	8.19	52.7	105.6	113.0	4512	16.00	221.4	3270	12.21	1.0200	262.7	297.9

TABLE. 2.5 (Continued).

Test No.	Feed Rate lbs/hr	Evapo-ration lbs/hr	Ini-tial Feed Temp.	Tube Top Temp. °F	Max. Liquid Temp. °F	q	Δt_m °F	U	q_B	Δt_B °F	Boiling Area. sq.ft.	U_B	h_B
28.	31.12	10.22	59.0	103.3	111.9	5200	16.47	247.7	4097	13.90	0.9970	295.8	341.2
29.	33.98	9.28	56.3	103.8	112.6	4956	15.92	244.2	3680	13.08	1.0200	275.9	315.1
30.	35.24	8.33	53.1	105.6	113.0	4714	15.42	240.0	3314	12.00	0.9970	277.3	316.9
31.	36.30	8.70	57.2	104.5	112.8	4786	15.79	237.8	3440	12.90	0.9970	264.9	300.8
32.	37.18	9.70	54.9	104.2	112.6	5273	16.20	255.3	3845	12.84	1.0200	293.5	338.2
33.	37.92	8.44	59.0	105.5	113.4	4707	14.15	261.0	3325	11.70	0.9970	285.1	327.0
34.	38.56	9.84	62.6	103.8	112.6	5183	15.93	255.3	3883	13.00	0.9970	299.9	346.7
35.	39.01	8.26	55.4	105.3	112.8	4746	16.16	230.3	3265	12.13	0.9270	290.5	334.2
36.	40.00	8.65	59.0	104.7	112.6	4841	16.90	224.5	3405	12.44	0.9505	288.3	331.3
37.	40.24	8.39	55.4	104.7	113.0	4829	15.81	239.8	3286	12.40	0.9737	272.5	310.6
38.	42.97	8.32	54.5	105.3	113.4	4924	15.73	245.6	3242	11.88	0.9737	280.5	321.0
39.	43.40	9.53	54.7	104.5	113.0	5417	15.81	268.9	3734	13.28	0.9737	288.9	332.1
40.	44.24	9.14	50.2	104.7	112.6	5405	16.01	264.8	3583	12.18	0.9505	310.0	360.3
41.	45.86	8.36	51.1	105.3	113.4	5130	17.20	234.0	3240	11.72	0.9505	290.9	334.7
42.	49.32	9.12	53.2	104.7	113.2	5494	16.71	257.8	3531	11.87	0.8925	333.9	393.0
43.	50.75	8.28	50.4	105.6	113.4	5303	15.97	260.3	3188	11.36	0.8925	314.5	366.3
44.	51.17	8.92	56.3	104.9	112.8	5384	16.16	261.2	3455	11.97	0.8575	337.0	397.3
45.	52.21	8.82	55.4	105.1	112.8	5403	16.71	253.6	3409	11.88	0.8346	344.0	407.0
46.	52.77	8.82	53.6	105.1	112.6	5479	15.81	272.0	3422	11.82	0.8575	337.9	398.7
47.	55.01	7.38	48.2	106.9	114.1	5196	16.86	241.8	2805	11.17	0.7880	319.0	372.4
48.	59.64	8.94	59.0	104.9	112.6	5564	16.36	266.8	3422	12.20	0.8575	327.4	384.0
49.	61.61	7.98	44.2	106.3	113.4	5814	16.90	270.0	3020	10.87	0.7416	375.0	451.0
50.	63.99	7.89	48.7	106.0	113.6	5702	17.25	259.5	2965	10.94	0.7185	377.4	454.5
51.	66.76	7.01	55.4	106.7	114.3	5197	16.67	244.5	2572	10.66	0.6955	347.2	411.5
52.	67.66	7.66	52.2	106.5	113.9	5620	16.63	265.3	2853	10.51	0.6955	390,8	474.4
53.	69.94	7.44	55.4	106.5	113.7	5476	18.00	238.5	2756	10.73	0.6725	380.2	458.5
54.	74.65	7.45	43.3	106.9	113.7	6190	18.15	267.5	2755	10.73	0.6490	395.8	481.5
55.	84.82	8.17	53.6	106.5	113.9	6375	18.44	271.2	2977	10.72	0.6258	444.1	555.3

TABLE. 2.6

TOLUENE IN COPPER-TUBE, NATURAL-CIRCULATION, EVAPORATOR.
Heating Water at 80°C. Total Heat Transfer Area = 1.275 sq.ft.

Test No.	Feed Rate lbs/hr	Evapo-ration. lbs/hr.	Ini-tial Feed Temp. °F.	Tube Top Temp. °F.	Max. Liquid Temp. °F.	q	Δt_m °F	U	q_B	Δt_B °F	Boiling Area. sq.ft.	U_B	h_B
1.	42.52	31.60	57.2	156.4	166.1	7045	18.82	293.8	5055	12.24,	0.9970	414.9	509.9
2.	43.45	30.92	54.5	157.3	165.8	7043	20.30	272.2	4966	13.79	0.9970	361.5	431.8
3.	44.34	28.28	57.2	156.6	165.1	6582	20.54	251.3	4525	13.45	0.9505	354.2	421.4
4.	44.54	30.60	58.1	156.2	166.3	6945	19.92	273.6	4875	13.85	0.9970	353.5	420.4
5.	47.56	27.83	55.0	157.3	165.8	6702	19.57	268.9	4437	12.71	0.9270	376.6	453.7
6.	48.98	30.10	57.2	156.9	165.8	7084	20.30	274.0	4799	12.76	0.9970	377.2	454.1
7.	49.29	29.65	59.9	156.4	166.5	6953	19.92	274.0	4698	13.24	0.9737	364.5	436.1
8.	50.33	29.53	53.6	156.6	166.7	7117	19.84	281.5	4669	12.65	0.9737	378.2	455.5
9.	51.22	28.72	59.9	156.6	166.1	6882	19.80	272.9	4545	12.81	0.9505	373.3	448.5
10.	52.27	27.11	55.4	157.5	166.1	6781	19.62	271.4	4296	12.12	0.9505	373.0	448.2
11.	52.38	29.24	58.5	157.1	166.1	7057	20.12	275.1	4735	12.45	0.9737	391.0	474.5
12.	52.50	28.78	58.1	157.1	166.7	6997	19.66	279.2	4546	12.40	0.9505	386.0	467.1
13.	54.16	28.24	57.6	157.1	166.3	6991	20.43	268.5	4463	12.89	0.9040	380.1	458.5
14.	54.73	28.80	59.5	156.9	166.3	7061	19.85	279.3	4551	12.60	0.9040	399.8	487.6
15.	54.90	28.05	53.6	156.6	166.5	7073	20.93	265.3	4408	12.45	0.9270	382.1	461.5
16.	55.62	28.10	50.9	157.3	166.7	7190	20.00	282.0	4420	12.02	0.9270	396.8	483.1
17.	56.94	29.36	55.4	158.0	167.0	7371	19.77	292.6	4641	11.92	0.8925	437.0	544.1
18.	57.79	27.55	53.6	157.6	166.7	7142	20.00	280.3	4262	12.00	0.9040	393.0	477.3
19.	57.90	28.40	56.1	157.1	166.7	7214	20.23	279.9	4464	12.24	0.9270	393.8	478.5
20.	58.99	27.95	56.3	157.3	166.5	7183	20.43	276.0	4393	12.38	0.9040	392.9	477.3

TABLE. 2.6 (Continued)

Test No.	Feed Rate lbs/hr	Evaporation lbs/hr	Initial Feed Temp. °F	Tube Top Temp. °F	Max. Liquid Temp. °F	q	Δt_m °F	U	q_B	Δt_B °F	Boiling Area. sq.ft.	U_B	h_B
21.	59.25	27.25	56.3	157.6	166.5	7087	20.30	273.9	4282	12.22	0.9040	388.0	470.2
22.	60.72	26.27	56.7	158.4	166.7	7004	19.76	278.2	4134	11.82	0.8346	419.6	517.0
23.	62.39	29.15	55.0	156.9	166.5	7558	20.24	292.8	4568	12.66	0.8925	404.3	494.3
24.	62.56	27.81	58.1	157.6	166.8	7275	20.54	278.0	4355	11.75	0.8925	415.2	510.4
25.	64.86	25.76	54.5	158.4	167.0	7154	19.40	289.4	4018	11.22	0.8346	429.3	532.2
26.	66.03	28.05	55.4	157.6	167.0	7543	19.37	305.5	4378	11.96	0.7880	464.9	587.9
27.	67.30	26.40	53.6	158.2	167.0	7387	20.65	280.5	4107	11.61	0.8110	436.4	542.9
28.	69.62	25.90	53.6	158.7	167.2	7427	19.92	292.5	4025	11.25	0.7880	454.1	570.4
29.	71.41	26.76	57.6	158.4	167.2	7519	20.35	289.8	4154	11.25	0.7648	483.3	617.6
30.	71.75	28.55	59.5	158.4	167.0	7773	20.07	303.9	4458	11.47	0.7646	508.5	659.0
31.	72.10	27.30	61.3	158.4	167.0	7524	20.40	289.2	4249	11.92	0.8110	439.7	548.3
32.	75.04	27.64	59.0	158.2	167.2	7766	22.13	275.6	4276	11.49	0.8110	459.0	577.7
33.	75.95	27.60	59.4	158.9	167.7	7810	21.05	291.0	4277	11.32	0.7648	494.1	635.2
34.	76.35	26.82	58.1	158.7	167.4	7736	21.37	284.0	4149	11.05	0.7880	477.0	607.5
35.	80.68	25.08	55.0	159.3	167.7	7764	21.53	283.0	3854	10.87	0.7416	478.8	610.5
36.	83.25	26.62	54.0	159.3	167.7	8165	22.65	282.6	4095	11.02	0.7185	517.6	674.7
37.	84.78	24.38	59.0	159.8	167.7	7696	22.23	271.7	3736	10.59	0.7185	491.2	630.5
38.	90.08	26.48	54.3	159.6	167.5	8452	22.81	290.5	4457	10.66	0.6490	645.0	909.0
39.	91.75	25.85	53.6	160.4	167.9	8477	21.82	304.8	3967	9.94	0.6955	574.0	774.0
40.	93.65	24.15	54.5	160.9	167.9	8273	21.80	298.0	3708	8.30	0.6490	689.0	999.0

CORRELATION.

The only variable which was altered to a large extent, in these investigations with each liquid, was the feed rate. It varied by several hundred per cent, while other conditions were roughly constant. To find the effect of feed rate on h_B , a plot of h_B vs. Feed Rate was made for all the liquids , on log-log paper (Fig. 2.4). The curve for water in Copper Tube seems to show a well-defined minimum, while values for alcohol and toluene increase with feed rate. Since no linear relationship was obtained, the points were next set out on a semilog paper (Fig. 2.41). No straight line was obtained even here. A plot of Evaporation (in lbs./hr.) vs. Feed Rate gave a separate curve for each liquid (Fig. 2.42). The curves are nearly straight lines for all liquids and have approximately the same negative slope. A plot of 'q' vs. Feed Rate (Fig. 2.43) gave similar curves for all the liquids.

To find the effect of the amount of vapour on the boiling film coefficient, h_B , the values of the latter were plotted against Evaporation (in lbs./hr.) on log-log paper (Figs. 2.5 and 2.51). Since in no case the total variation in the amount of vapour formed was more than 50 %,

BOILING FILM COEFFICIENT
VS.
FEED RATE

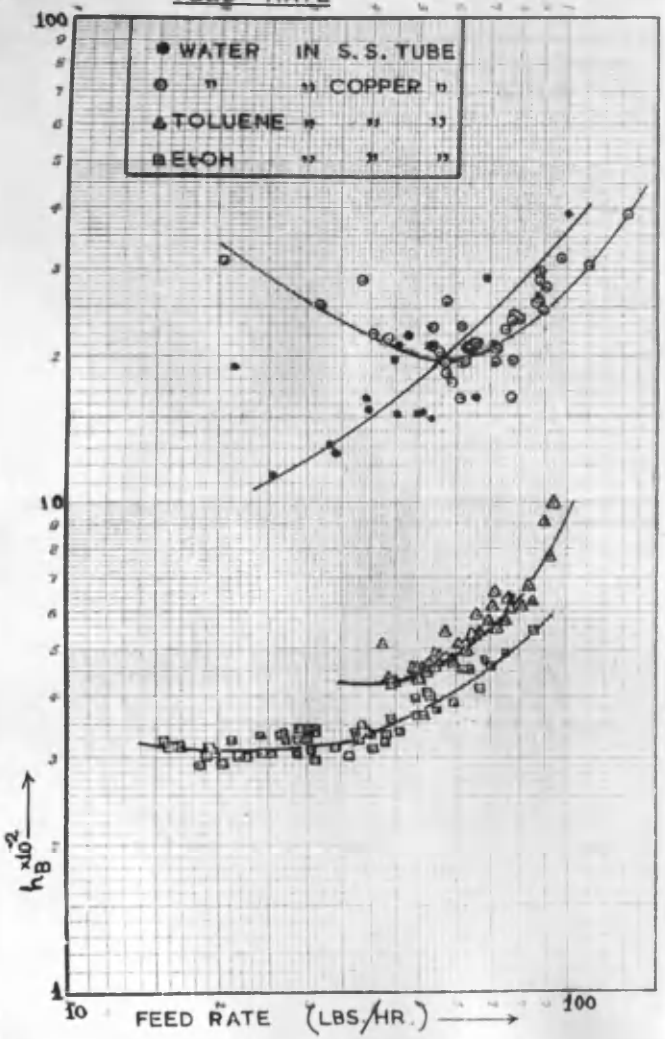
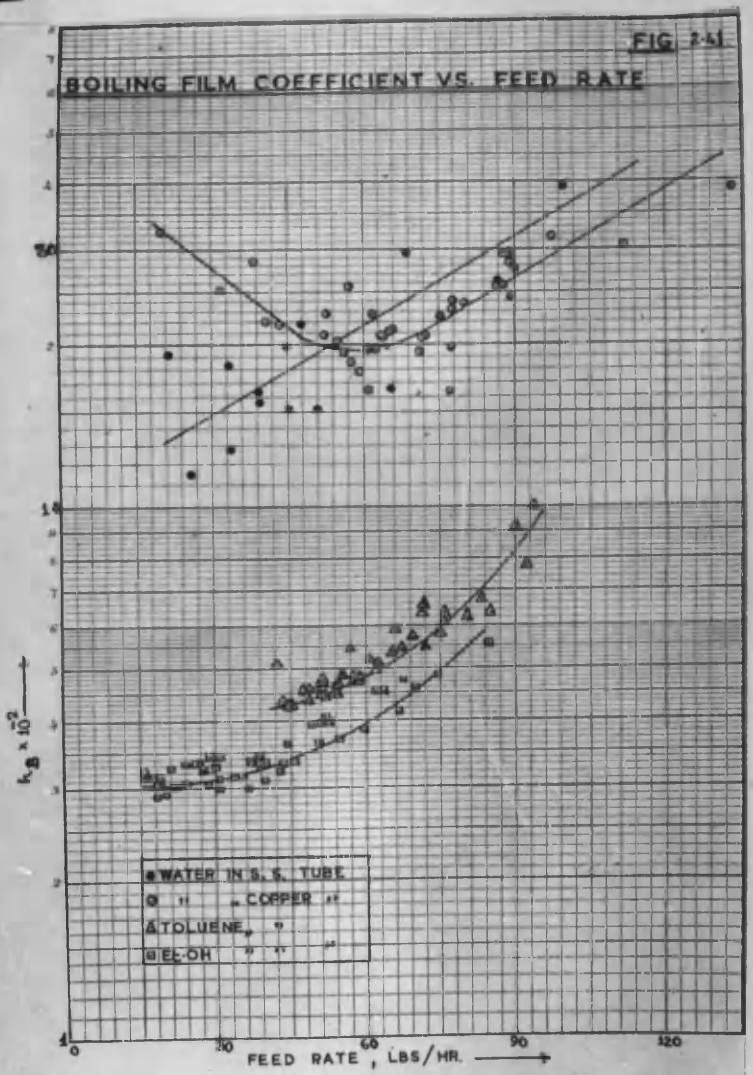


FIG. 2·4.

FIG 2·5

BOILING FILM COEFFICIENT VS. FEED RATE



the points are mostly huddled together, generally spread vertically one above the other, showing that for the same amount of vapour formed, the coefficient could vary widely on account of other factors.

DISCUSSION.

The most important fact that comes out of these investigations is that for a given pressure in the tube and a roughly constant temperature drop, the heat load per hour, q, shows very little change with increasing feed rate. Even when the feed rate has been varied by several hundred per cent for each liquid, the variation in "q" is seldom more than 20% and only in a few cases as high as 50%. If these few cases be left out of account, it would seem that the tube would transmit the same amount of heat per hour, whatever the feed rate, provided that the pressure in the system and temp.drop are constant and provided also that boiling does occur in a part of the tube. Since "Δt_m" and "q" are roughly constant, the value of U, the average overall heat transfer coeff. for the entire tube, also varies only to a small extent. The effect of feed rate on evaporation (in lbs/hr) is also small, as will be seen from Fig.2.42. With increasing feed rate, the coeffs. show a slight tendency to decrease at first and then to rise. In the

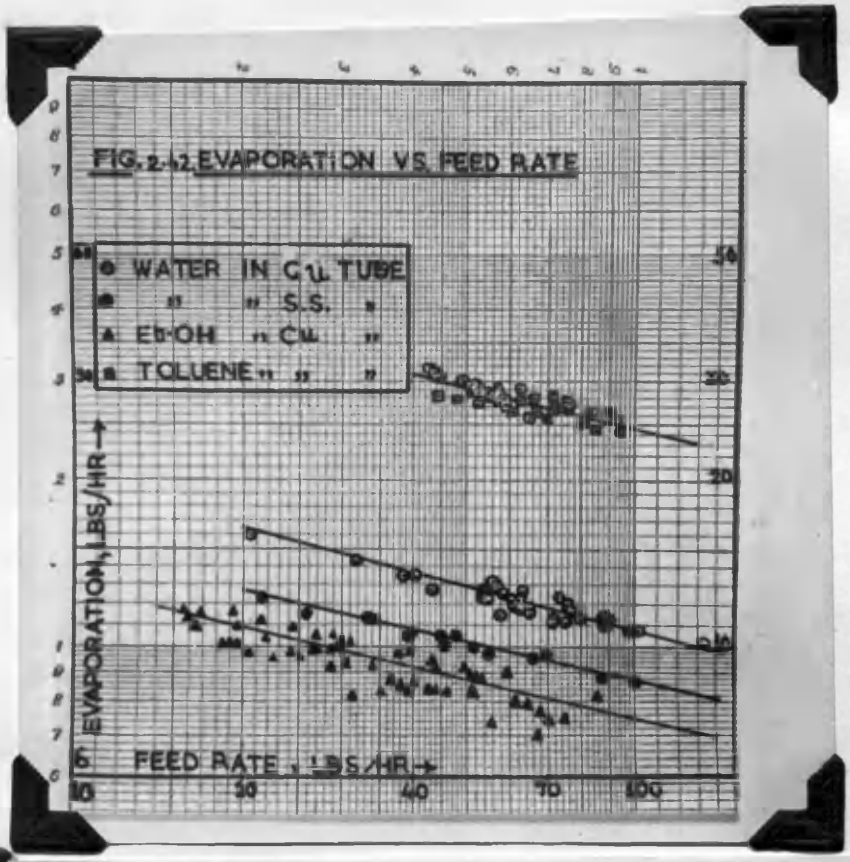


FIG. 2.42 EVAPORATION VS FEED RATE
WATER IN Cu TUBE
" " S.S. "
Et-OH " Cu "
TOLUENE " " "
EVAPORATION, LBS/HR →
FEED RATE, LBS/HR →

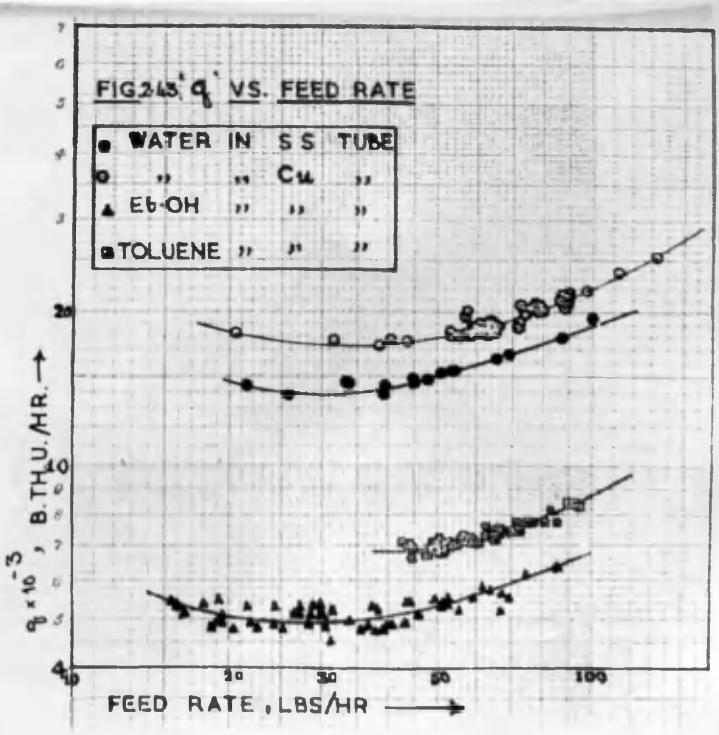


FIG 2.43 q VS. FEED RATE
WATER IN S S TUBE
" " Cu "
Et-OH " " "
TOLUENE " " "
q x 10^-3, B.TH.U./HR. →
FEED RATE, LBS/HR →

case of water in copper tube, this tendency is very well marked. In the case of the other two liquids, the tendency is there though not so pronounced.

It is suggested, therefore, that when the percentage evaporation and also the actual evaporation (in lbs/hr) are high, the effect of the vapour predominates. There is a high fluid velocity in the tube and the Boiling Film Coeffs. are high. On increasing the feed rate, the amount of evaporation diminishes slightly and then remains rather steady over a considerable range, and, therefore, the boiling film coeff. shows some decrease at first and then remains more or less unchanged. At high feed rates, it appears that the liquid also becomes sufficient in quantity to contribute considerably to the velocity in the boiling section and more than compensates for the loss in evaporation by increasing the coefficient above the value obtained with moderate feed rates. In the experiments on the glass-tube evaporator it was observed that at high feed rates the liquid in the boiling section was in a state of violent agitation - very much more than when the feed rate was low. This difference in the behaviour of the liquid in the boiling section under low and high feed rates, respectively, would suggest a rough analogy with the difference that exists in the viscous and turbulent motions of fluid in a tube.

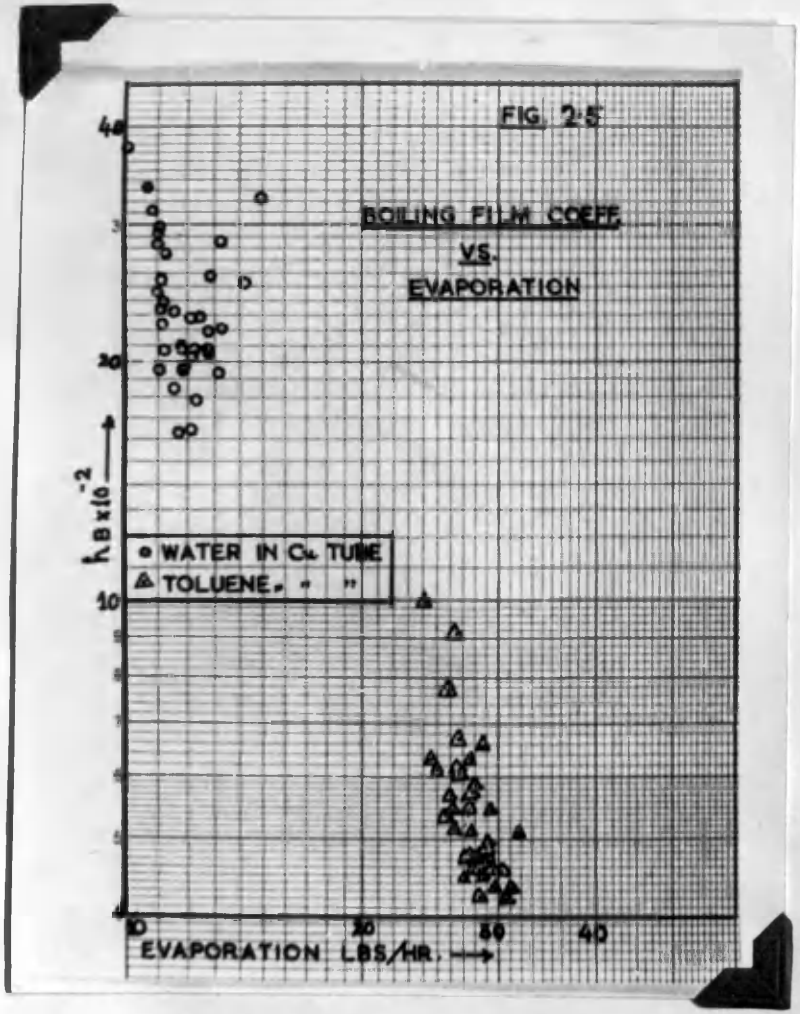


FIG. 2·5
BOILING FILM COEFF.
VS.
EVAPORATION
WATER IN Cu TUBE
TOLUENE " "
EVAPORATION LBS/HR.

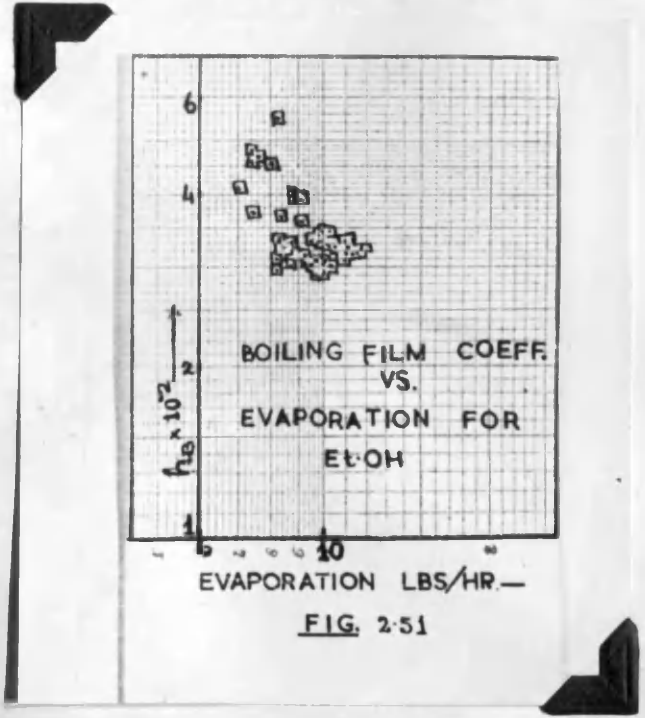

BOILING FILM COEFF.
VS.
EVAPORATION FOR
Et·OH
EVAPORATION LBS/HR.—

FIG. 2·51

With rising feed rate, the values of q_B, the heat load in the boiling section, and the boiling area decrease steadily. The mean value of the overall temp. drop for the boiling section, Δt_B, remains mostly unchanged except at vey high feed rates when it falls rather rapidly.

The coefficients for water are the highest. The values of the boiling film coefficient are generally of the same order as those obtained by Stroebe[45] et al under parallel conditions of boiling temp. and temp. drop, using a very much larger tube in which boiling occurred throughout its length. In the present investigations on water the temperature drop across the boiling liquid film varied between 4.1°F and 7.77°F, as found by back-calculation on the basis of q_B, h_B and the boiling area.

The coeffs. for toluene are higher than those for ethyl alcohol, and coeffs. for either are very much lower than those for water. As in the case of the glass-tube evaporator, it is very probable that the higher molar fraction evaporated in the case of toluene must have induced proportionaltely higher velocities than obtained in the case of ethyl alcohol. For Toluene the molar fraction evaporated per hour ranged from 0.263 to 0.344, whereas for ethyl alcohol it ranged from 0.152 to 0.252. This would mean about 50% higher velocity in the case of

toluene under similar conditions. This difference must be partly responsible for the higher coeffs. obtained with toluene.

.....
%%%%%%%

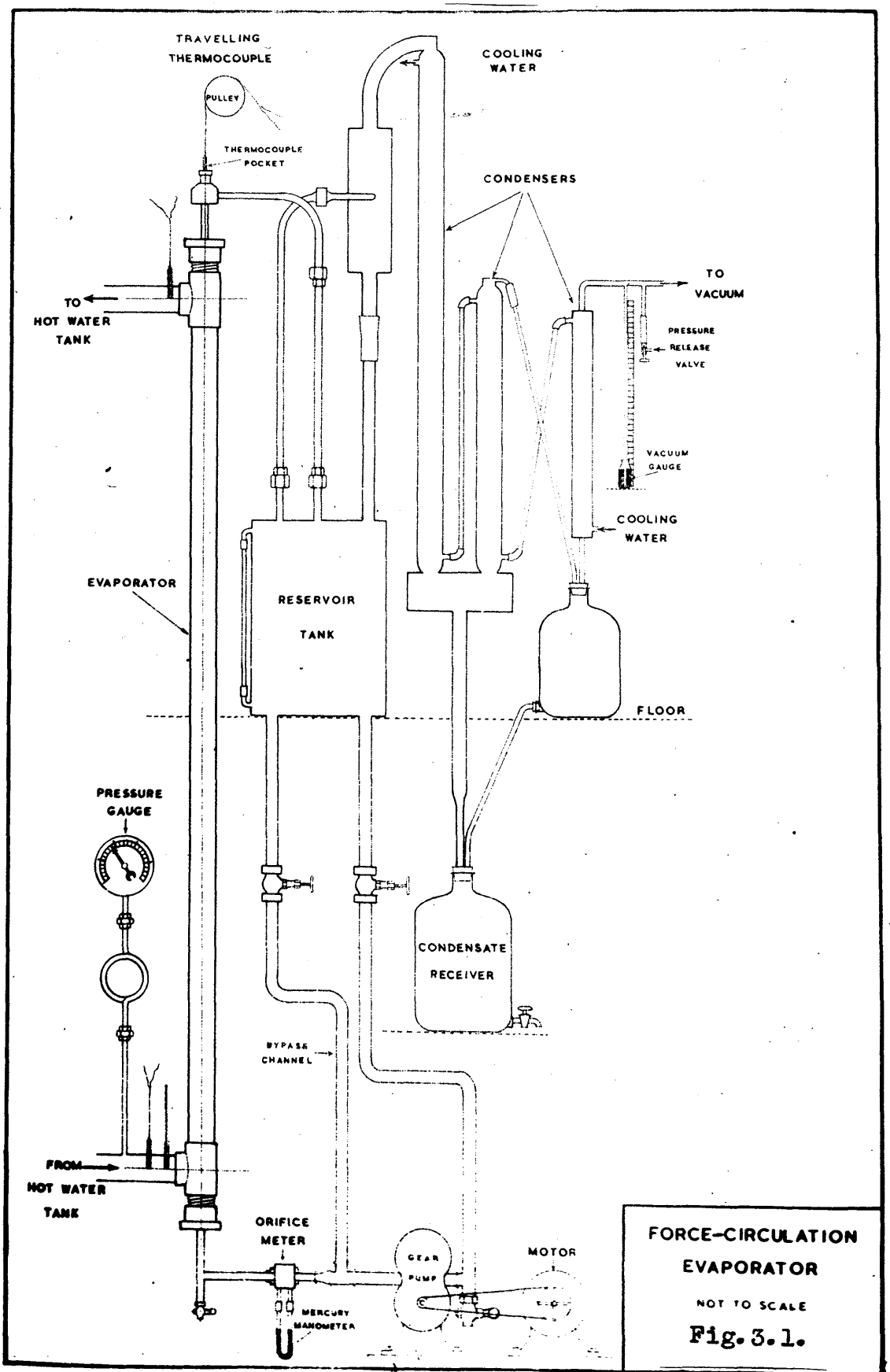
C H A P T E R. III.

THE COPPER-TUBE, FORCED-CIRCULATION, EVAPORATOR.

C H A P T E R III.

COPPER-TUBE, FORCED-CIRCULATION, EVAPORATOR.

The copper-tube evaporator described in the last chapter was now converted into a forced-circulation evaporator for studying heat transfer to the same liquids as used before, under non-boiling conditions, and thus to investigate effects of boiling in a vertical tube in promoting heat transfer. This necessitated some alterations in the apparatus. The new set-up is shown in Fig. 3.1 (see also Plate III - I). A side-tube was soldered to the bottom of the evaporator tube and connected to the outlet of a ratary pump through an Orifice Flowmeter shown in Fig. 3.11. A feed tank, about 7.5 gallon capacity, was connected to the outlet from the brass gland-piece at the top of the evaporator tube, to the inlet and drain-pipe of the separator, and to the inlet and outlet tubes of the rotary pump. By means of the valve on the pipe connecting the feed tank to the outlet of the rotary pump, the feed rate could be controlled by bye-passing some or none of the feed to the tank. The feed tank also served as the primary separator. Three condensers had to be used to deal with the large amount of evaporation obtained. A tap provided at the bottom of the evaporator and that of the inlet to the feed



FORCE-CIRCULATION EVAPORATOR

NOT TO SCALE

Fig. 3.1.

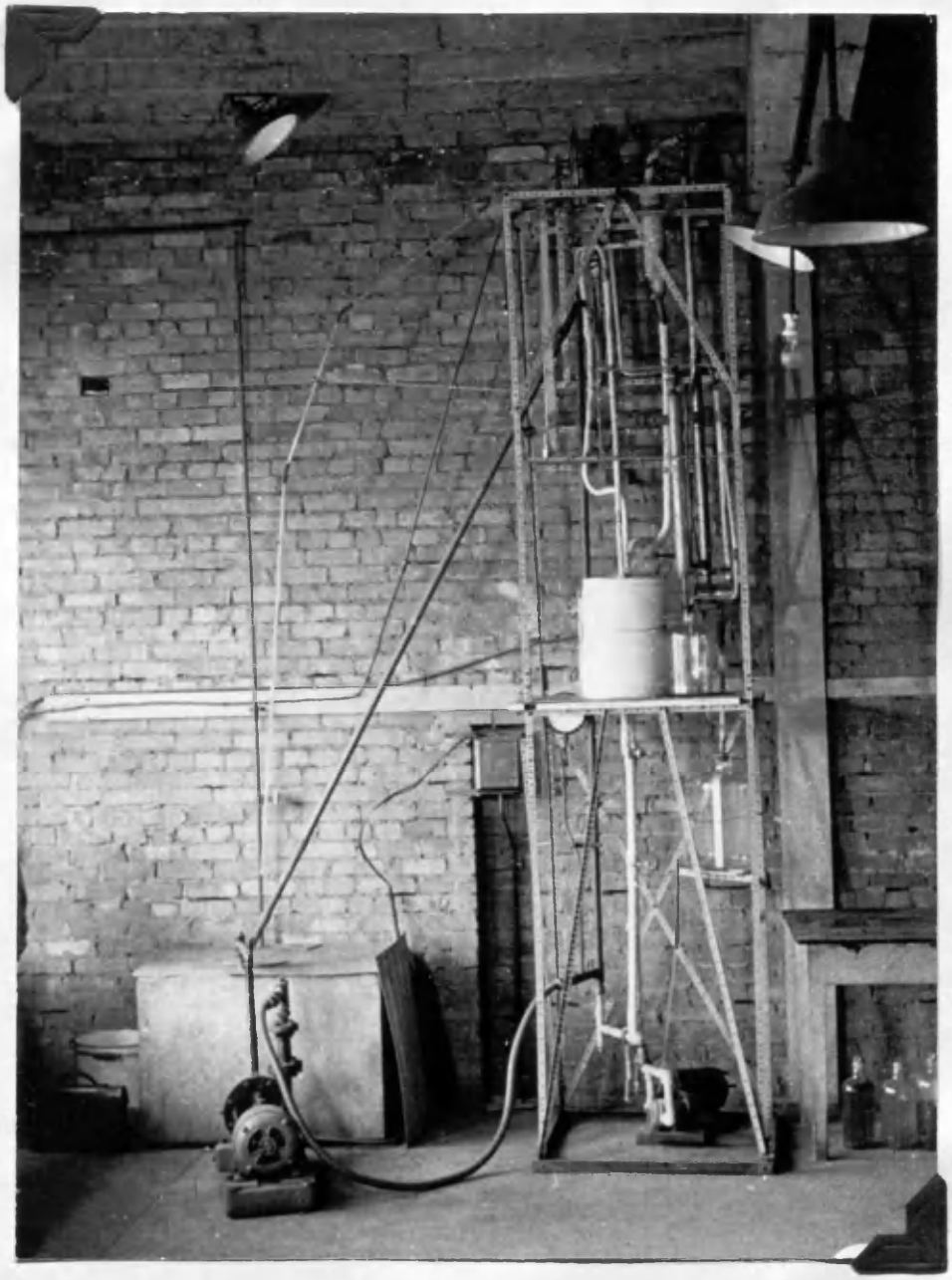


Plate. III-I. Forced-Circulation Evaporator.

pump, enabled the system to be emptied when necessary. The feed could be sucked into the tank through the inlet tap of the pump.

CALIBRATION OF THE ORIFICE FLOWMETER:-

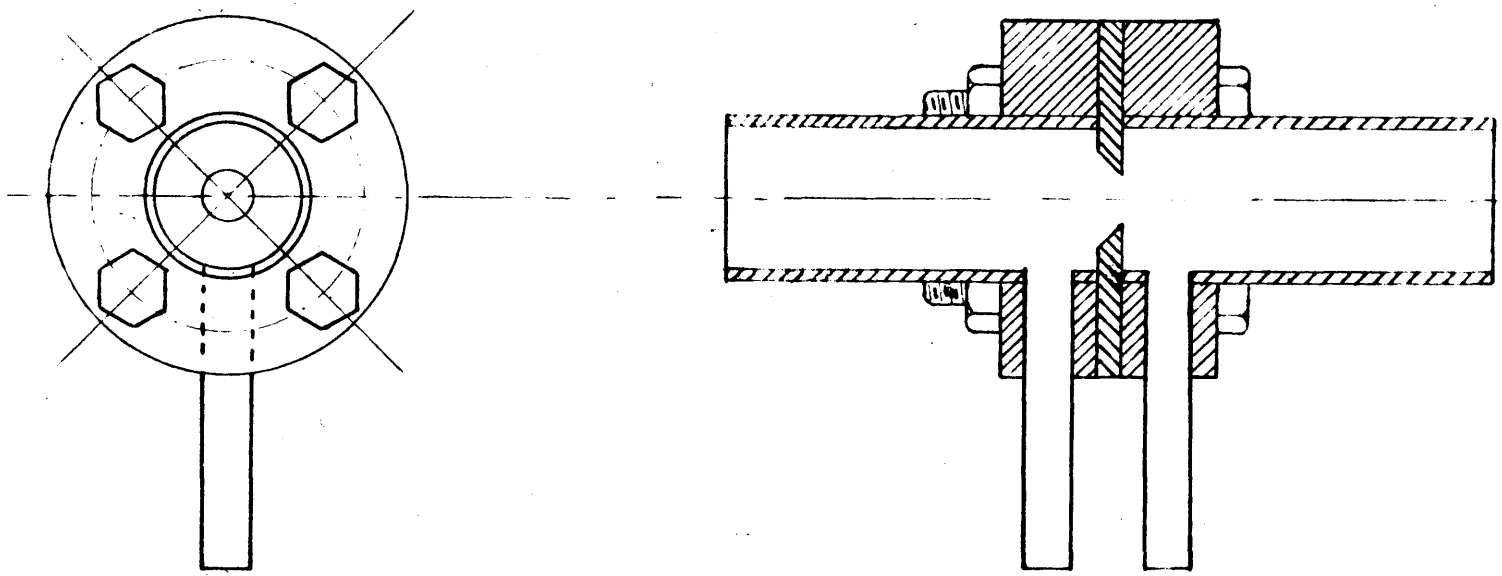
The orifice-meter was calibrated for each of the liquids used, viz., water, 95.6% ethyl alcohol, and toluene. The calibration curves are shown in Figs. 3.2, 3.21, and 3.22, respectively.

EXPERIMENTAL PROCEDURE:-

Hot water at 80°C in experiments on water and toluene, and at 50°C in experiments on ethyl alcohol, was circulated through the heating jacket. The desired pressure was established in the system, the feed pump started and the bye-pass valve was adjusted to give the desired rate of flow. When conditions became steady, the experiment was started. Two traverses of the travelling thermocouple were made, as usual, and the amount of condensed vapour collected during the period of the experiment noted.

CALCULATIONS:-

Knowing the amount of condensate and the latent heat of the liquid, the heat transferred per hour, q, was calculated. Latent heats were taken from the same sources as in the last two Chapters.



ORIFICE METER

FULL SCALE

FIG - 3·11

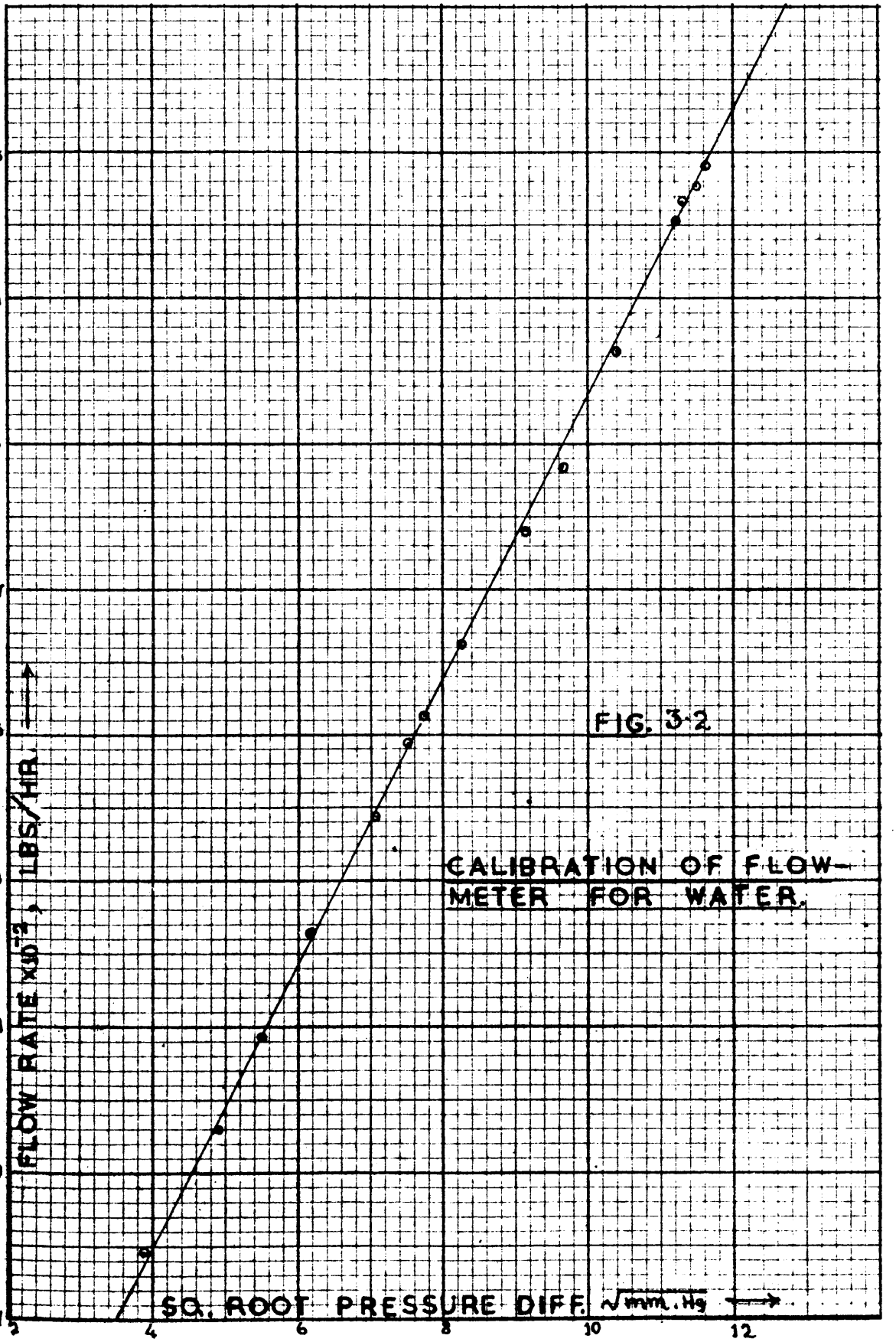


FIG. 3·2

CALIBRATION OF FLOW-METER FOR WATER.

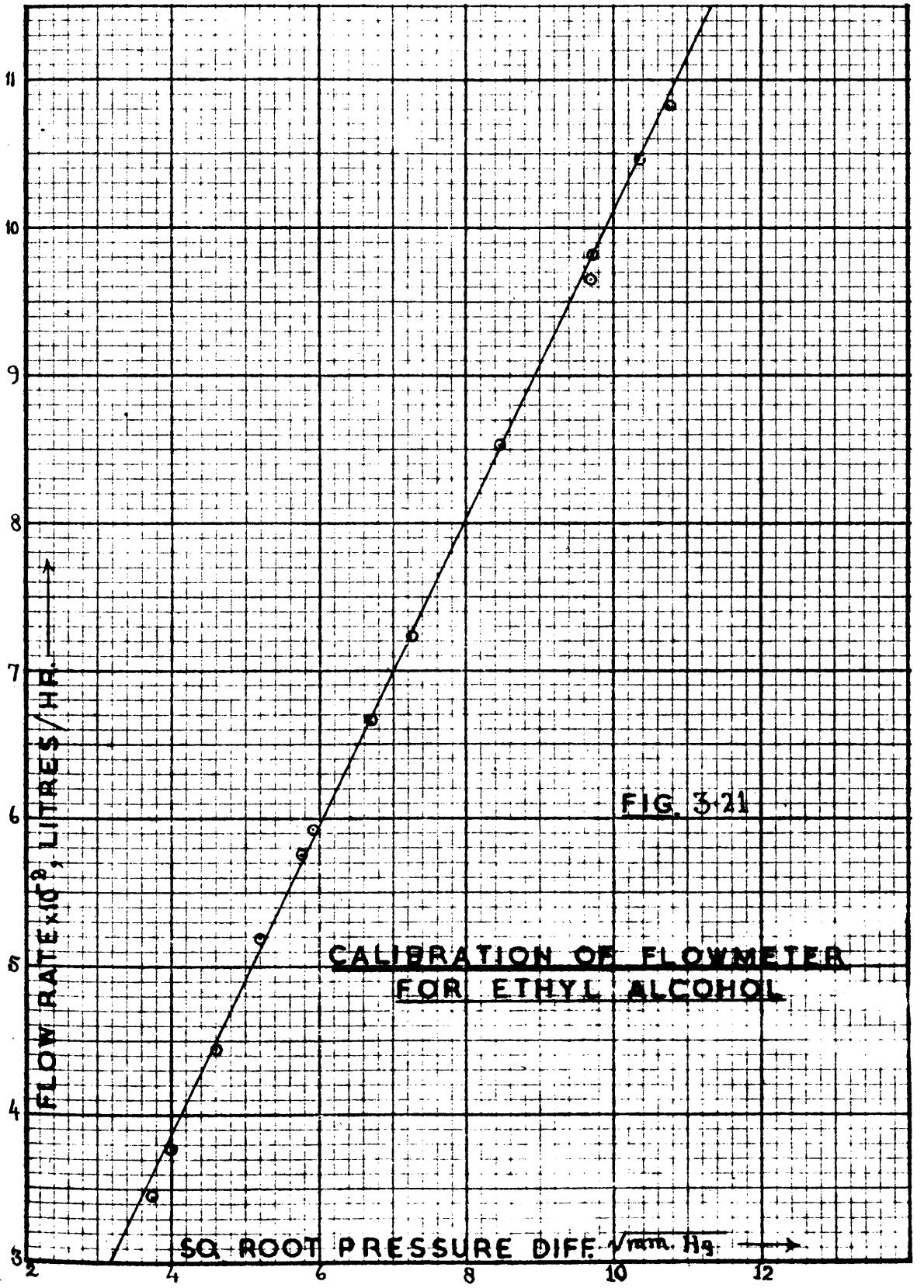


FIG. 3.21

CALIBRATION OF FLOWMETER FOR ETHYL ALCOHOL

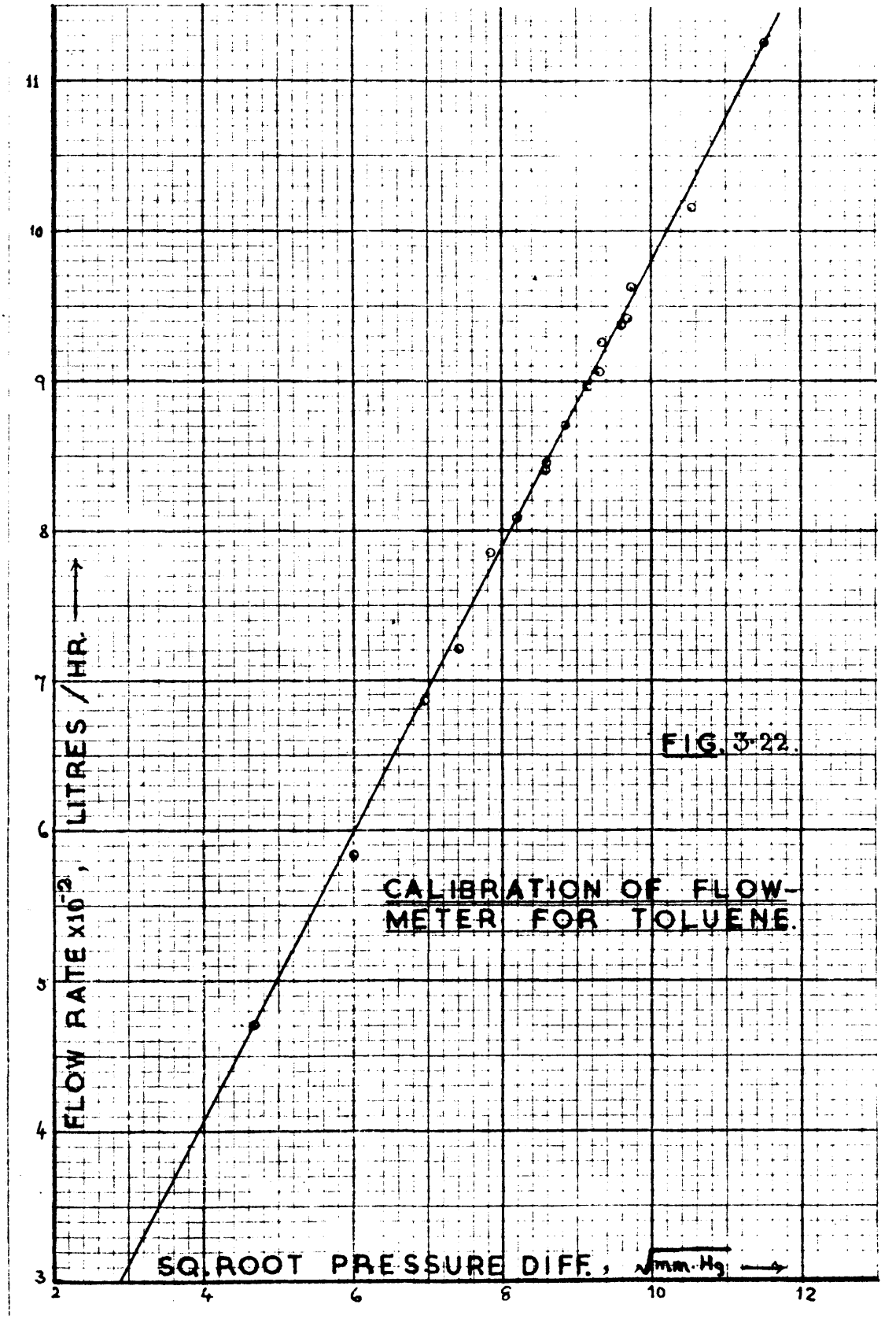


FIG. 3·22.

CALIBRATION OF FLOW-METER FOR TOLUENE.

For finding Δt_m, a plot of Δt vs. distance from the bottom of the tube was made and Δt_m found as before. The curves obtained had no minimum, showing that no marked boiling occurred in any of the tests. A typical curve is shown in Fig. 3.3.

RESULTS:-

These are given in tables 3.1, 3.2, and 3.3, respectively, for water, 95.6% ethyl alcohol and nitration quality toluene. Contrary to the results obtained with the Natural-Circulation Evaporators (Chapters I and II), the coeffs. for toluene are lower than those for alcohol under similar conditions of temp. drop and liquid velocity. The coeffs. for water are the highest. With all the three liquids, the values of Δt_m and liquid velocities used are of the same order.

CORRELATION.

Velocity being the major variable used with each liquid, values of the film coefficient, h, were first plotted against liquid velocity (Fig.3.31). The curves for all the liquids are very nearly straight lines with an average slope of 1.1. For a more accurate estimation of the relation between 'h' and $DV\rho/\mu$, therefore, the Tables 3.11, 3.21, and 3.31 were first prepared. Table 3.11 was prepared by group-

TABLE. 3.1.

WATER IN COPPER TUBE FORCED CIRCULATION EVAPORATOR.

Heating Area = 1.275 sq.ft. Heating Water at 80°C. in all tests.

Test No.	Feed Rate lbs/hr	Temp. in Separator. °F.	Evaporation lbs/hr	Evaporation. %	q	Δt_m °F	U	h	Velocity ft/sec.
1.	785	158.4	7.73	0.985	7770	11.38	535	681	2.98
2.	825	159.1	7.94	0.963	7980	11.15	561.5	724	3.13
3.	930	159.0	9.86	1.06	9910	11.46	678	930	3.53
4.	962	155.7	11.64	1.21	11700	13.01	705.5	987	3.65
5.	990	158.5	11.50	1.06	10550	11.90	696	965.5	3.76
6.	992	155.2	12.89	1.30	12960	13.49	754	1079	3.76
7.	1055	156.4	12.03	1.14	12090	12.75	744	1059	4.00
8.	1075	157.9	10.92	1.015	10975	12.35	697.5	967.5	4.08
9.	1101	156.6	12.90	1.17	12970	12.87	790	1155	4.17
10.	1138	155.0	14.54	1.28	14620	14.12	812	1208	4.32
11.	1165	159.0	11.98	1.03	12050	11.82	799	1174	4.42
12.	1188	158.5	11.90	1.002	11960	11.84	792.5	1160	4.50
13.	1195	159.0	12.24	1.024	12305	11.92	810	1190	4.53
14.	1293	154.4	16.20	1.254	16300	14.35	891	1384	4.90
15.	1310	159.4	12.11	0.925	12170	11.79	810	1190	4.97
16.	1385	159.0	13.23	0.956	13300	11.96	872.5	1340	5.25
17.	1400	158.2	13.70	0.98	13765	12.50	864.5	1322	5.31
18.	1410	155.5	16.54	1.17	16620	14.08	926	1471	5.35
19.	1467	155.0	17.87	1.22	17980	14.35	983	1620	5.56
20.	1475	157.5	15.22	1.03	15300	12.98	924	1466	5.59
21.	1480	159.1	14.21	0.96	14280	12.24	916.5	1447	5.61
22.	1485	155.0	17.87	1.204	17980	14.29	987	1631	5.62
23.	1500	160.4	13.29	0.887	13355	11.58	904	1412	5.69
24.	1537	157.8	15.88	1.034	15960	12.87	973.5	1595	5.81
25.	1540	155.2	18.51	1.202	18620	14.19	1029	1749	5.84

TABLE. 3.1 (Continued).

Test No.	Feed Rate lbs/hr	Temp. in Separator. °F.	Evaporation lbs/hr	Evaporation %	q	Δt_m °F	U	h	Velocity. ft/sec.
26.	1580	159.1	14.44	0.913	14520	12.25	930	1481	5.99
27.	1599	156.6	17.74	1.11	17830	13.49	1036	1770	6.07
28.	1600	155.8	18.65	1.165	18750	14.42	1020	1723	6.07
29.	1630	156.6	16.58	1.017	16660	13.72	953	1540	6.18
30.	1650	157.3	16.93	1.025	17020	13.22	1010	1695	6.26
31.	1700	159.4	15.35	0.903	15430	12.14	998	1660	6.45
32.	1700	157.3	17.20	1.01	17290	13.40	1012	1701	6.45
33.	1710	159.0	15.16	0.887	15240	12.60	948	1527	6.49
34.	1710	155.5	19.85	1.16	19950	14.54	1076	1888	6.49
35.	1717	158.0	17.38	1.012	17470	13.10	1046	1799	6.51
36.	1737	157.0	18.52	1.067	18600	13.72	1064	1852	6.59
37.	1790	156.8	17.86	0.998	17950	13.42	1050	1810	6.79
38.	1795	155.7	20.16	1.122	20260	14.54	1093	1942	6.81
39.	1796	156.3	18.96	1.055	19060	13.84	1081	1906	6.81
40.	1800	159.4	14.39	0.80	14460	11.70	970	1585	6.83
41.	1850	157.9	17.90	0.968	17990	13.12	1076	1890	7.02
42.	1853	157.5	18.98	1.024	19060	13.49	1109	1965	7.03
43.	1860	158.0	18.08	0.97	18170	13.18	1082	1901	7.05
44.	1890	159.4	16.67	0.883	16760	12.27	1072	1876	7.17
45.	1916	157.3	19.85	1.036	19940,	13.76	1137	2085	7.27
46.	1940	159.1	16.67	0.86	16760	12.62	1041	1784	7.36
47.	1945	157.6	18.89,	0.972	18990	13.43	1109	1993	7.37
48.	1960	157.6	19.13	0.976	19230	13.33	1131	2066	7.43
49.	1980	157.5	18.75	0.948	18850	13.38	1105	1980	7.51
50.	1980	157.9	18.80	0.949	18895	13.53	1095	1949	7.51
51.	1982	157.0	20.16	1.017	20250	13.86	1147	2120	7.51
52.	1990	159.1	17.65	0.887	17740	12.47	1117	2021	7.55
53.	2000	158.9	20.98	1.049	21100	13.00	1273	2594	7.59

TABLE. 3.1 (Continued)

Test No.	Feed Rate lbs/hr	Temp. in Separator. °F	Evaporation lbs/hr	Evaporation. %	q	Δt_m °F	U	h	Velocity. ft/sec.
54.	2028	156.1	21.43	1.056	21540	14.40	1173	2210	7.69
55.	2048	157.7	19.65	0.959	19730	13.81	1120	2029	7.77
56.	2065	157.0	22.05	1.067	22150	13.93	1248	2492	7.84
57.	2086	157.8	19.84	0.951	19930	13.41	1166	2185	7.91
58.	2106	157.8	19.49	0.925	19580	13.38	1148	2127	7.99
59.	2125	157.6	20.10	0.946	20200	13.35	1188	2263	8.05
60.	2135	157.6	20.28	0.950	20390	13.45	1190	2269	8.09
61.	2165	158.0	19.94	0.922	20050	13.28	1185	2253	8.21
62.	2175	159.1	17.65	0.811	17740	12.61	1104	1976	8.25
63.	2213	158.4	19.93	0.901	20030	13.14	1196	2293	8.39
64.	2223	157.6	20.28	0.913	20380	14.82	1080	1902	8.43
65.	2252	158.0	19.94	0.885	20050	13.26	1187	2260	8.55
66.	2280	156.4	25.17	1.117	25300	15.40	1290	2665	8.65
67.	2282	158.2	23.99	1.051	24070	13.58	1390	3131	8.66
68.	2300	160.4	17.90	0.778	17990	11.65	1212	2352	8.72
69.	2322	156.3	22.75	0.980	22860	14.66	1224	2398	8.81
70.	2325	155.7	23.14	0.995	23250	14.73	1238	2452	8.82
71.	2340	159.3	18.52	0.792	18620	12.39	1179	2229	8.87
72.	2410	156.6	23.94	0.994	24040	14.62	1290	2665	9.14

TABLE. 3.2.

ETHYL ALCOHOL IN COPPER-TUBE, FORCED-CIRCULATION EVAPORATOR.
Heating Water at 50°C. Heat Transfer Area = 1.275 sq. ft.

Test No.	Feed Rate lbs/hr	Evaporation lbs/hr	Evaporation %	Temp. in Separator. °F	q	Δt_m °F	U	h	Velocity ft./sec.
1.	841	7.48	0.890	106.7	3141	11.79	209.1	230.7	4.05
2.	977	8.36	0.856	106.5	3510	11.36	242.5	272.2	4.70
3.	979	9.86	1.007	105.2	4139	12.49	260.0	294.5	4.71
4.	1021	9.45	0.925	105.6	3969	11.74	265.4	301.4	4.92
5.	1016	10.96	1.078	105.6	4603	12.42	291.0	334.9	5.33
6.	1110	11.12	1.002	105.3	4670	12.86	284.7	326.6	5.34
7.	1131	10.43	0.922	106.3	4382	11.92	288.5	331.6	5.45
8.	1157	10.78	0.931	106.0	4526	11.93	297.8	343.9	5.58
9.	1183	10.90	0.921	105.0	4578	12.47	288.2	331.1	5.69
10.	1305	12.18	0.933	105.8	5114	12.74	314.8	366.9	6.29
11.	1352	12.57	0.930	105.3	5280	12.24	338.7	399.5	6.51
12.	1363	13.22	0.970	105.8	5554	12.60	345.6	409.1	6.56
13.	1396	12.88	0.923	105.6	5412	12.77	332.3	390.8	6.72
14.	1406	13.98	0.995	106.3	5870	12.28	375.2	451.3	6.77
15.	1472	13.84	0.940	106.5	5814	12.07	378.0	455.3	7.09
16.	1481	14.53	0.982	105.3	6106	12.74	375.8	452.3	7.13
17.	1484	15.05	1.014	105.3	6319	12.96	382.5	461.9	7.19
18.	1524	14.26	0.936	105.6	5990	12.09	388.7	471.3	7.34
19.	1532	14.40	0.940	105.8	6047	12.55	378.1	455.5	7.35
20.	1584	13.22	0.834	107.3	5554	11.38	382.7	462.3	7.63
21.	1587	13.84	0.872	106.0	5814	12.07	378.0	455.3	7.65
22.	1589	15.22	0.958	105.6	6390	12.64	396.7	482.9	7.65

TABLE. 3.2 (Continued)

Test No.	Feed Rate lbs/hr	Evapo-ration lbs/hr	Evapo-ration %	Temp. in Sepa-rator. F.	q	Δt_m ^oF	U	h	Velocity. ft./sec.
23.	1592	14.61	0.918	106.5	6139	12.05	399.7	487.3	7.67
24.	1604	15.60	0.972	105.8	6564	12.87	400.1	488.1	7.73
25.	1630	15.43	0.946	105.6	6480	12.73	399.2	486.6	7.85
26.	1642	14.27	0.869	107.2	5976	11.60	404.1	494.0	7.91
27.	1684	15.71	0.934	105.6	6590	12.34	419.1	516.5	8.11
28.	1695	15.64	0.923	106.5	6566	12.24	421.3	520.0	8.16
29.	1700	15.22	0.895	107.1	6394	11.75	427.0	528.5	8.19
30.	1719	15.22	0.885	106.0	6394	12.32	407.6	499.3	8.27
31.	1727	16.61	0.963	106.3	6976	12.67	432.0	536.1	8.31
32.	1744	15.22	0.873	106.5	6392	11.59	433.0	537.9	8.39
33.	1748	15.91	0.911	106.7	6681	12.03	436.0	542.3	8.41
34.	1770	16.34	0.923	106.2	6865	12.57	428.6	531.0	8.52
35.	1794	16.61	0.925	105.9	6976	12.40	441.6	551.0	8.64
36.	1803	16.08	0.892	105.4	6756	12.40	427.6	529.3	8.68
37.	1811	16.13	0.891	106.5	6777	12.06	441.0	550.2	8.73
38.	1837	16.61	0.904	107.1	6976	11.83	462.5	583.8	8.85
39.	1863	16.68	0.895	106.3	7004	12.15	452.4	568.2	8.97
40.	1899	16.41	0.865	105.3	6891	12.01	450.0	564.4	9.14
41.	1906	16.74	0.879	106.7	7030	12.03	458.6	578.0	9.17
42.	1924	15.79	0.821	106.7	6633	11.25	462.6	584.2	9.26
43.	1927	17.45	0.906	106.9	7329	11.99	479.7	611.7	9.27
44.	1934	16.88	0.873	106.3	7087	11.98	464.2	586.9	9.31
45.	1949	16.62	0.853	107.1	6985	11.75	466.3	589.9	9.38

T A B L E. 3.3

TOLUENE IN COPPER-TUBE, FORCED-CIRCULATION EVAPORATOR.

Heating Water at 80°C. Total Heat Transfer Area = 1.275 sq.ft.

Test No.	Feed Rate lbs/hr	Evaporation lbs/hr	Evaporation %	Temp. in Separator °F.	q	Δt_m °F	U	h	Velocity ft/sec.
1.	741	12.92	1.744	157.1	2145	13.14	128.0	135.0	3.29
2.	774	13.62	1.760	155.8	2260	13.42	132.1	139.5	3.44
3.	831	14.60	1.758	157.8	2424	12.60	150.8	160.5	3.69
4.	833	14.83	1.780	157.8	2461	12.53	154.1	164.2	3.70
5.	857	12.54	1.464	159.4	2082	11.61	140.6	149.0	3.81
6.	859	14.68	1.710	158.0	2435	12.48	153.1	163.0	3.81
7.	995	17.86	1.796	157.8	2965	12.51	186.0	201.0	4.42
8.	1105	20.60	1.866	155.8	3420	11.62	230.7	254.1	4.91
9.	1118	21.30	1.906	158.2	3533	12.44	222.8	244.6	4.97
10.	1150	21.38	1.858	158.5	3545	12.22	227.6	250.4	5.10
11.	1206	21.90	1.816	158.5	3635	12.40	230.o	253.3	5.35
12.	1206	22.13	1.834	159.0	3705	12.20	238.3	263.4	5.36
13.	1314	26.11	1.988	157.6	4335	12.75	266.5	298.0	5.83
14.	1362	28.31	2.080	157.8	4700	12.66	291.0	329.3	6.05
15.	1373	26.60	1.938	156.7	4412	13.34	259.2	289.2	6.10
16.	1415	23.95	1.692	161.2	3974	11.04	282.5	318.5	6.29
17.	1417	28.78	2.030	157.9	4780	12.84	291.8	330.3	6.29
18.	1437	28.30	1.970	156.0	4698	13.76	368.0	302.0	6.38
19.	1489	29.75	1.998	157.8	4935	13.25	292.0	330.6	6.61
20.	1512	29.63	1.960	158.4	4916	13.15	293.3	332.3	6.71

TABLE. 3.3 (Continued).

Test No.	Feed Rate lbs/hr	Evaporation lbs/hr	Evaporation %	Temp. in Separator. °F	q	Δt_m °F	U	h	Velocity ft./sec.
21.	1552	31.01	1.998	156.0	5144	13.72	294.3	336.6	6.89
22.	1561	30.50	1.956	158.5	5060	12.21	325.3	374.0	6.93
23.	1581	30.32	1.918	159.1	5030	12.46	316.5	362.4	7.02
24.	1591	28.90	1.816	159.8	4798	11.93	315.1	360.6	7.07
25.	1593	35.15	2.206	156.2	5835	13.60	336.5	388.9	7.08
26.	1621	28.50	1.758	161.3	4732	10.92	340.2	393.8	7.20
27.	1690	31.90	1.889	158.2	5296	12.78	325.0	373.6	7.50
28.	1708	37.42	2.192	158.9	6210	12.67	384.5	454.4	7.59
29.	1726	30.78	1.784	158.4	5110	11.84	338.5	391.5	7.67
30.	1766	34.10	1.932	159.4	5668	12.13	366.0	428.8	7.84
31.	1776	39.41	2.219	156.6	6540	13.44	382.0	450.9	7.89
32.	1792	39.35	2.196	159.1	6530	12.38	414.0	496.1	7.96
33.	1800	33.76	1.876	160.9	5601	11.49	382.5	451.6	7.99
34.	1809	29.75	1.644	161.2	4938	11.28	343.0	397.6	8.03
35.	1833	38.05	2.075	157.5	6310	12.97	382.0	451.0	8.14
36.	1884	31.65	1.681	160.7	5250	11.40	361.0	422.0	8.37
37.	1889	34.37	1.820	158.5	5700	12.30	364.0	426.0	8.39
38.	1891	37.23	1.969	160.5	6180	12.08	401.0	477.6	8.40
39.	1908	41.90	2.197	155.7	6950	13.44	406.0	484.7	8.47
40.	1917	47.40	2.472	154.4	7861	15.18	406.0	484.7	8.51
41.	1947	33.26	1.710	160.9	5520	11.33	382.0	451.0	8.65
42.	1964	34.30	1.748	158.4	5690	12.11	368.5	431.8	8.72
43.	1975	34.40	1.743	161.1	5710	11.55	387.8	459.0	8.77
44.	1990	58.14	2.922	155.3	9654	14.98	505.0	632.8	8.84
45.	1992	43.50	2.185	159.0	7220	12.03	471.0	580.3	8.85

TABLE. 3.11.

(Derived from Table No. 3.1, for Water).

Feed Rate lbs/hr	Temp. in Separator. °F.	Average Liquid Temp. °F	h	V ft/sec	Re (DVρ/μ)	$(Re)^{1.1}$	$\frac{hD}{k}$	$\frac{C\mu}{k}$	$\frac{\frac{hD}{k}\times 10^3}{(Re)^{1.1}}$	h (Calc.)	$\frac{h_{calc.}}{h}$
898	158.1	163.2	858	3.41	31010	84110	85.5	2.55	1.017	1319	1.54
1072	156.2	161.9	1093	4.07	36590	104600	109.2	2.57	1.044	1513	1.39
1230	159.1	162.6	1220	4.67	42260	122600	121.7	2.57	0.994	1689	1.39
1427	157.0	161.8	1440	5.41	48700	143300	144.2	2.58	1.006	1896	1.32
1508	157.5	162.0	1567	5.71	51560	152600	156.4	2.57	1.025	1984	1.27
1612	157.1	161.6	1642	6.11	54900	163500	164.0	2.58	1.003	2081	1.27
1708	157.8	161.8	1755	6.48	58290	174700	175.2	2.58	1.003	2190	1.25
1784	157.0	161.6	1819	6.77	60720	182600	181.6	2.58	0.995	2260	1.24
1874	158.0	161.8	1943	7.10	63920	193300	194.0	2.58	1.004	2332	1.20
1961	157.9	161.7	1954	7.43	66840	203000	195.1	2.58	0.961	2442	1.25
2019	157.7	161.5	2195	7.62	68660	209200	219.2	2.57	1.048	2498	1.14
2103	157.6	161.5	2267	7.97	71450	218400	226.5	2.57	1.038	2579	1.14
2206	158.2	161.6	2137	8.37	75050	230600	213.4	2.57	0.926	2678	1.25
2302	157.4	161.0	2599	8.73	78000	240600	259.8	2.58	1.080	2769	1.07
2375	157.9	161.5	2447	9.01	80720	249800	244.5	2.58	0.979	2839	1.16

T A B L E. 3.21.

(Derived from Table No. 3.2, for Ethyl Alcohol)

Test No.	Feed Rate lbs/hr	Temp. in Separator. °F.	Average Liquid Temp., °F.	h	V ft/sec.	Re (DVρ/μ)	$Re^{1.1}$	$\frac{hD}{k}$	$\frac{C\mu}{k}$	$\frac{hD}{k} \times 10^3 / (Re)^{1.1}$
1.	841	106.7	109.7	230.7	4.05	13150	33950	92.9	15.49	2.740
2.	977	106.7	110.1	272.2	4.70	15280	40040	109.6	15.44	2.737
12.	1363	105.8	108.9	409.1	6.56	21200	57400	164.8	15.51	2.871
13.	1396	105.6	108.7	390.8	6.72	21720	58970	157.3	15.52	2.666
25.	1630	105.6	108.8	486.6	7.85	25350	69900	195.9	15.52	2.804
26.	1642	107.2	109.9	494.0	7.91	25690	70910	198.9	15.44	2.806
44.	1934	106.3	109.5	586.9	9.31	30250	84880	236.4	15.47	2.784
45.	1949	107.1	109.7	589.9	9.38	30490	85620	237.5	15.49	2.775

T A B L E. 3.31.

(Derived from Table No. 3.3, for Toluene)

1.	741	157.1	162.4	135.0	3.29	28490	79470	62.71	4.61	0.789
5.	857	159.4	163.9	149.0	3.81	32980	93350	69.23	4.62	0.742
10.	1150	158.5	163.2	250.4	5.10	44260	129000	116.15	4.63	0.900
15.	1373	156.7	162.2	289.2	6.10	52800	156600	134.4	4.61	0.859
20.	1512	158.4	162.3	332.3	6.71	58170	174300	154.4	4.61	0.886
30.	1766	159.4	163.4	428.8	7.84	67960	206800	199.2	4.62	0.963
40.	1917	154.4	160.3	484.7	8.51	73700	226100	225.1	4.62	0.995
41.	1947	160.9	164.2	451.0	8.65	74900	230100	209.6	4.62	0.912
42.	1964	158.4	163.4	431.8	8.72	75530	232200	200.1	4.62	0.862
43.	1975	161.1	163.9	459.0	8.77	76020	233800	213.4	4.62	0.913
45.	1992	159.0	163.5	580.3	8.85	76700	236200	269.7	4.62	1.144

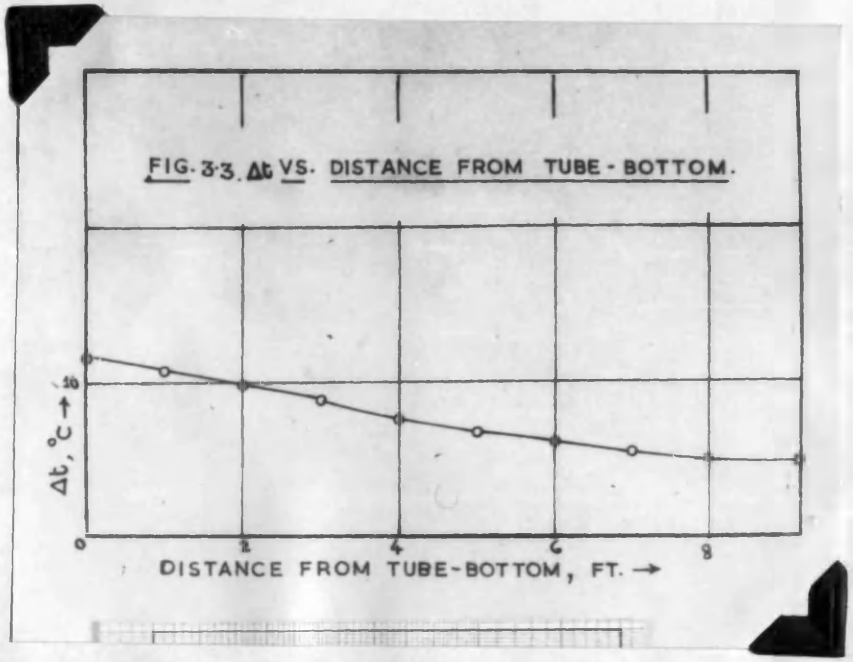


FIG. 3·3. Δt VS. DISTANCE FROM TUBE-BOTTOM.
Δt, °C →
20
0
2
4
6
8
DISTANCE FROM TUBE-BOTTOM, FT. →

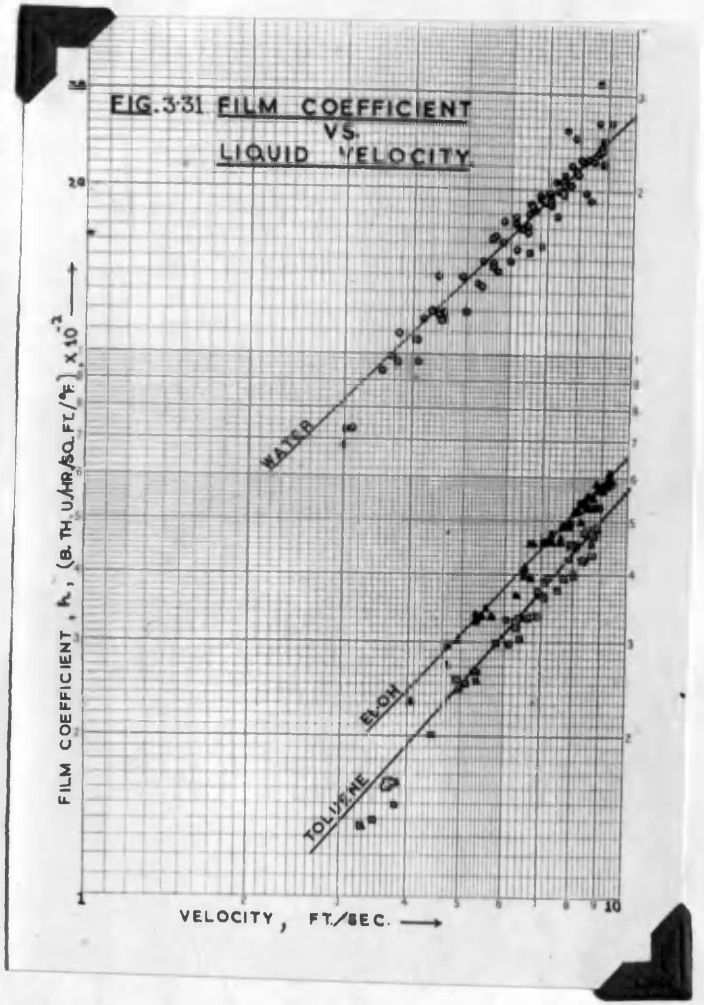


FIG. 3·31 FILM COEFFICIENT VS. LIQUID VELOCITY
FILM COEFFICIENT, h, (B.TH.U./HR./SQ.FT./°F.) X 10⁻²
WATER
ETOH
TOLUENE
VELOCITY, FT./SEC. →
1
10

ing the successive test data in Table 3.1 into fives and taking averages. For Tables 3.21 and 3.31, some of the test data were picked out at random from Tables 3.2 and 3.3, respectively. The serial numbers of these tests are given in the derived tables. This procedure was adopted to minimise calculations. For calculating the values of the various functions at the average liquid temperature in the evaporator tube, the nomographs and tables given in the Appendix of Ref. 3, were used. To obtain the viscosity of 95.6% ethyl alcohol at 68°F, the viscosities of ethyl alcohol of various percentage strengths from 100 downwards, given by Ref. 3, were plotted against percentage composition. From this curve the viscosity for 95.6% ethyl alcohol was read out. Then, assuming that the viscosity of 95.6% Et.OH varies with temperature in the same manner as that of the 100% liquid, the viscosity of 95.6% Et.OH at the required temperatures was calculated. The values obtained were

0.865 c.p. at 109°F, and

0.860 " " " 110°F.

A plot of h vs. Re was now made (Fig. 3.32). For each liquid a separate curve with a different slope was obtained. The slope for water is 1.03, for Et.OH it is 1.1 and for toluene it is 1.25. However, in an attempt at final correlation of the test data for all the liquids, an average slope

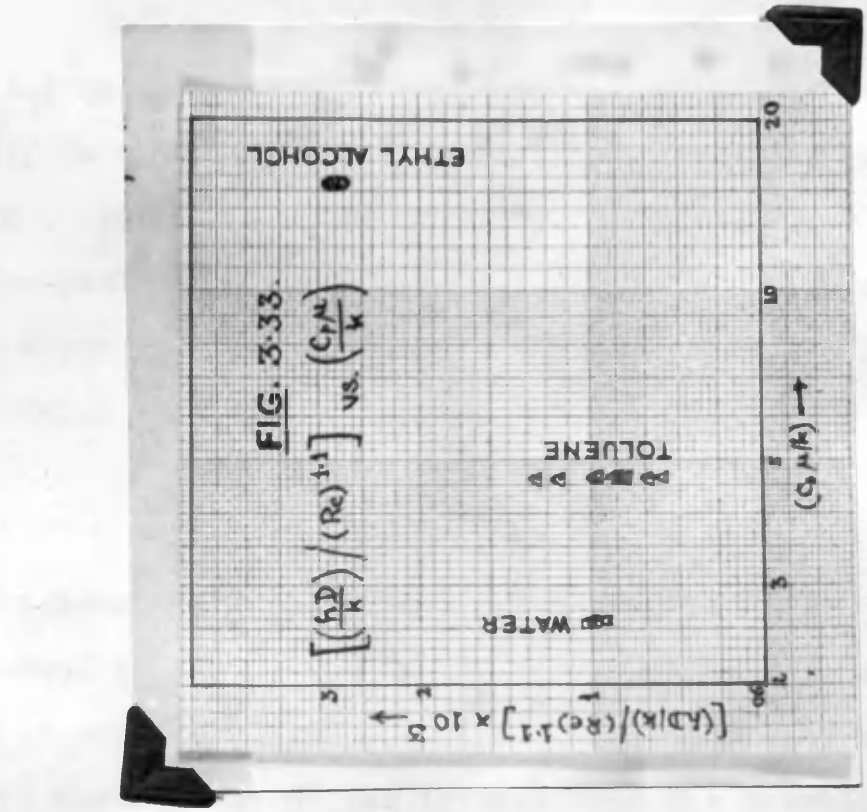


FIG. 3·33.
$\left[\left(\frac{hD}{k}\right)/(Re)^{1/3}\right]$ vs. $\left(\frac{C_p\mu}{k}\right)$
ETHYL ALCOHOL
WATER
TOLUENE
$[(hD/k)/(Re)^{1/3}] \times 10^{3}$
$(C_p\mu/k)$

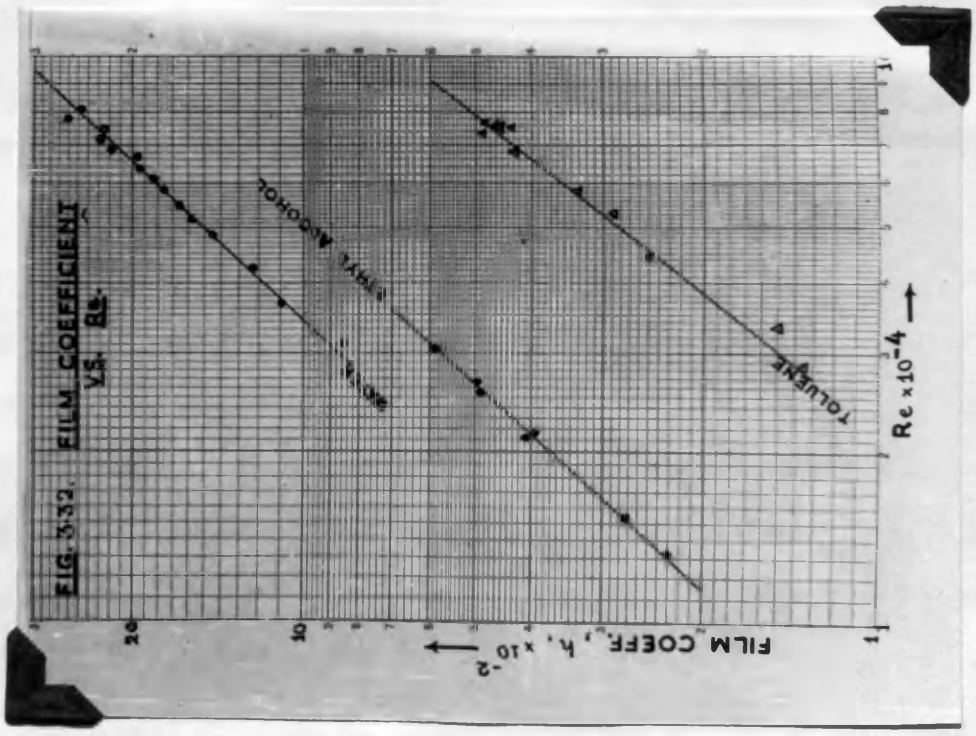


FIG. 3·32. FILM COEFFICIENT V.S. Re.
ETHYL ALCOHOL
TOLUENE
FILM COEFF., $h_i \times 10^{-2}$
$Re \times 10^{-4}$

of 1.1 was assumed for all the liquids and a plot of $(\frac{hD}{k})/(Re)^{1.1}$ vs. $(\frac{C_p\mu}{k})$ was made for the three liquids (Fig. 3.33). For each of water and alcohol the points are very close-packed, and for toluene, they are spread vertically one above the other. An examination of Table 3.31 shows that the value of the function,

$$\frac{\frac{hD}{k} \times 10^3}{(Re)^{1.1}},$$

for toluene varied from 0.742 to 1.144 - a total variation of about 50% - whereas in the case of water and ethyl alcohol it was only about 7%. It is probable that the lower power assumed for Re for toluene than the actual one of 1.25, as also the lower values of film coefficients, h, obtained for this liquid, were both responsible for this large variation obtained in the value of the above function for toluene. For water, although a higher power was assumed for Re than the actual (= 1.03), the high values of coeffs., h, must have partly masked the effect of the assumed power for Re for this liquid. For alcohol, the power of 1.1 used in the above calculations was the actual one. Had toluene given a cluster of points such that a straight line could be drawn through all the three clusters, it would have been possible to find the slope of the curve and give a general correlation, but the distribution of the points as obtained did not justi-

fy such a step.

DISCUSSION

The above attempt at correlation shows that a different law must be governing the heat flow to each of the three liquids. The variation of h as $Re^{1.03}$ even in the case of water is unusual. To find how far the results on water agreed with the Dittus-Boelter equation of the following form,

$$\frac{hD}{k} = 0.023\left(\frac{DV\rho}{\mu}\right)^{0.8}\left(\frac{C_p\mu}{k}\right)^{0.4} ,$$

the values of h were clculated from this Equation and were found to be uniformly higher than the experimentally determined values (see Table 3.11). The ratios of the clculated and observed values of h, $h_{calc.}/h$, are shown in the last column of Table 3.11. It will be seen that the calculated values are higher by 7 - 54%. In this respect the results on water agree qualitatively with those of Logan, Fragen and Badger[52] whose observed values for sugar solutions were lower than those predicted by the above equation with a constant equal to 0.0225.

Using the following equation,

$$\Delta t_m = \Delta t_A - \frac{\Delta t_A}{9.8(v)^{0.73}} \cdot \frac{N}{2} ,$$

given by Boarts et al[46] for the prediction of the average true

temperature drop, Δt_m, the latter was calculated for some of the tests on water. The calculated values obtained were much higher than the observed values. For example, for test Nos. 1, 12, 27, 40, and 72 (Table 3.1), the calculated values were higher ~~than~~ by 2.5°F, 3.0°F, 3.4°F, 2.9°F, and 2.9°F, respectively. The authors, who also found that the equation gave results one to two degrees high for Δt_m in their investigations, could not assign any reason for the discrepancy.

The important fact that comes out of these investigations, however, is that the boiling film coefficients in the vertical, natural-circulation, evaporator correspond to high fluid velocities of the order of 5 - 15 ft/sec. This is obvious from a study of Fig. 3.31 and Tables 2.4, 2.5, and 2.6 in Chapter II. In the case of toluene, the film coeffs. for forced-circulation become comparable with the boiling film coefficients only when the velocity of feed in forced-circulation has attained the value of 8 ft/sec. This lends support to the view, expressed in Chapters I and II, that the higher boiling coefficients obtained with toluene than with Et.OH might have been due to much higher velocities induced by higher molar fraction evaporated under natural circulation.

Another interesting result obtained is the fact that the percentage evaporation for any liquid is almost constant regardless of the feed rate.

C H A P T E R. IV.

BOILING LIQUIDS IN PARALLEL FLOW OVER HEATED HORIZONTAL WIRES.

CHAPTER IV.

BOILING LIQUIDS IN PARALLEL FLOW OVER HEATED HORIZONTAL WIRES

This chapter deals with investigations that have been made on liquids boiling over electrically-heated, horizontal wires, and flowing parallel to the latter.

Moscicki and Broeder (cited by Ref. 2) attempted to determine Critical Δt by using electrically heated wires. Nukiyama (cited by Refs. 2, 6, and 10) was the first to give a complete boiling curve using the same method. Farber and Scorah[7] used several wires to study boiling curves under various conditions. McAdams[6] et al used 4 different Pt wires both in the nucleate and the film boiling regions. In all these investigations the liquid was stagnant. It was, therefore, decided to study boiling on wires with the liquid under forced-circulation, parallel to the horizontal wire. Pt wires of 0.02 in., 0.01 in., and 0.005 in. dia. were used with water and 95.6% ethyl alcohol, the liquids circulating at three different velocities.

Description of the Apparatus.

The platinum wires were used both as the heat transfer surfaces and as Platinum Resistance Thermometers. The apparatus consisted of two main parts:-

(1) The Electrical System, and

(2) The Circulating System.

The Electrical System consisted of arrangements for obtaining regulated current through the experimental wire from a bank of accumulators, and for measuring the current strength and potential drop across the test section of the wire. The circuit diagram is shown in Fig. 4.111. Current drawn from the accumulators was regulated by a variable resistance. Its magnitude was determined by measuring the voltage drop across a semi-standard resistance made from 10 S. W.G., Low-Temperature-Coefficient-of-Resistance "Ferry" wire. There were two such semi-standards made, 0.1 ohm and 0.2 ohm, approximately. Each of them was calibrated against a precision resistor, using a Vernier Potentiometer, Type 4363, made by Messrs Tinsley and Co., London, S.E.25. Potential drops across the semi-standard and across the test section, in the actual experiments, were measured with a Students' Potentiometer whose diagram of connections is shown in Fig. 4.112. It is capable of measuring 0.01 mv. at 1 mv. The potentiometer

DIAGRAM OF ELECTRICAL CONNECTIONS.

FIG. 4·11.

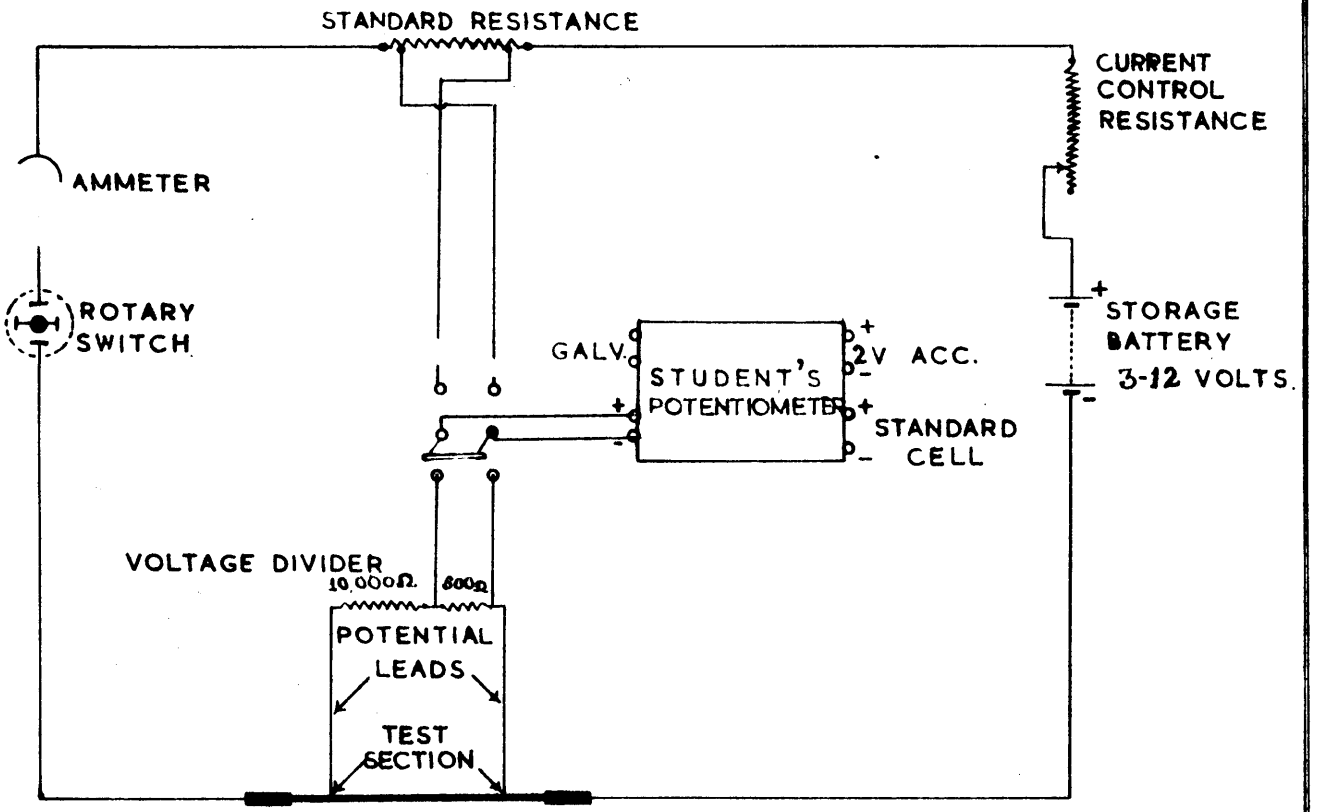
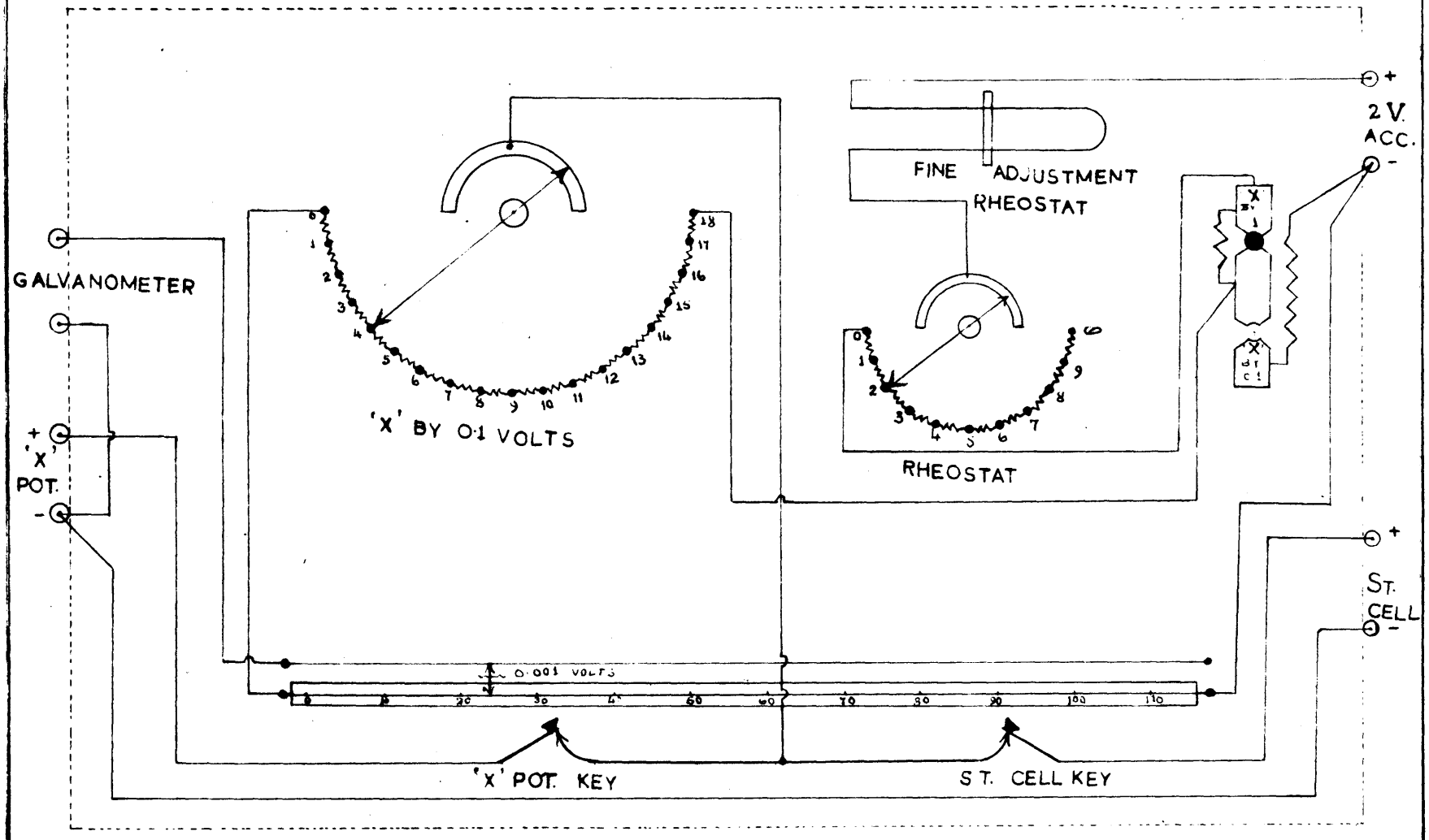


FIG. 4·112.

STUDENT'S POTENTIOMETER.

DIAGRAM OF CONNECTIONS.



was used in conjunction with a mirror galvanometer. Voltages were measured either directly or through a voltage divider depending upon their magnitude, the potentimeter being capable of measuring 1.91 volts directly.

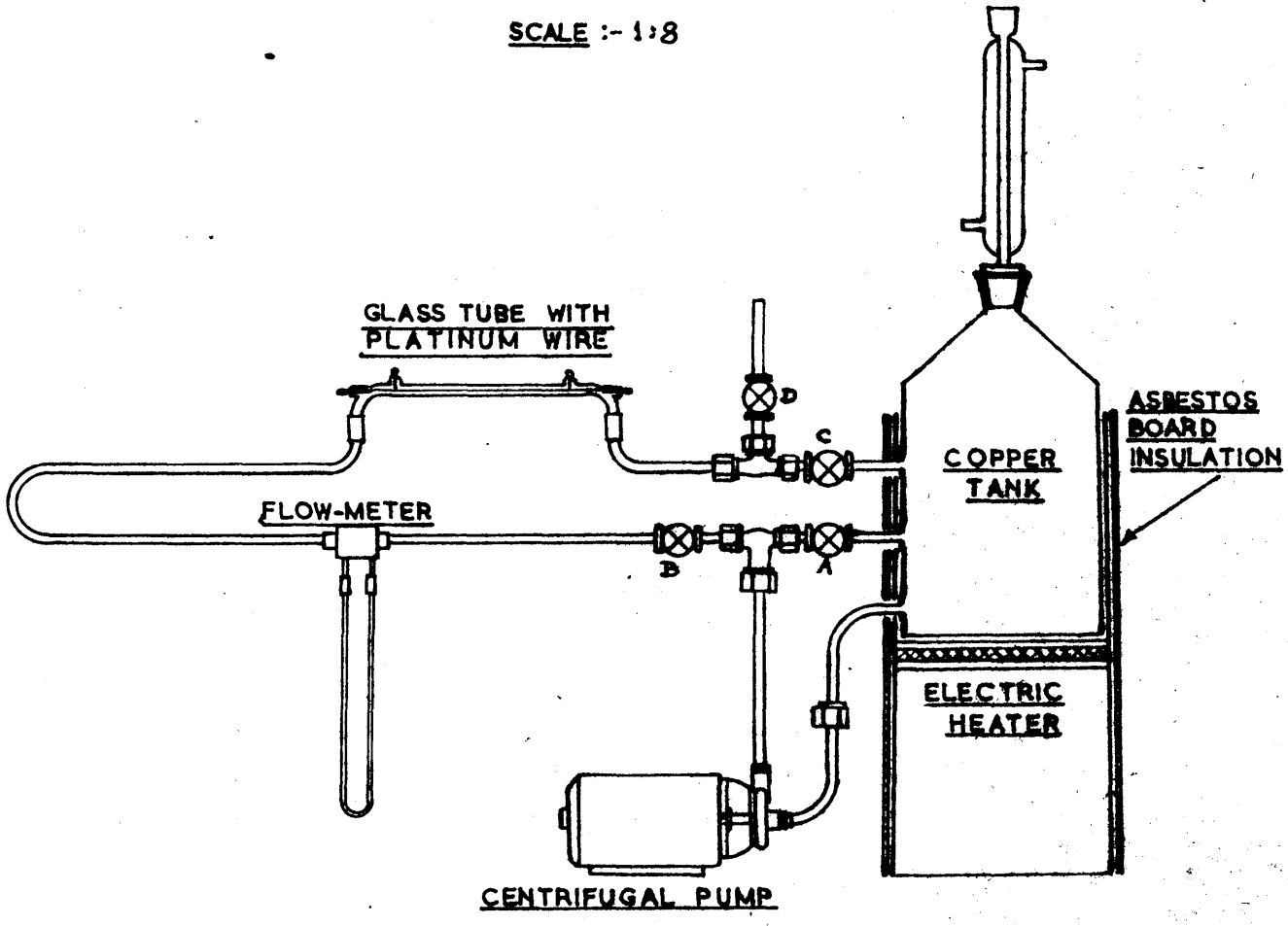
The Circulating System (Fig. 4.12 and Plate IV - I) was assembled from a copper vessel of about 2.3 gallon capacity, with a reflux condenser, a centrifugal pump, ½ in. i.d. copper tubes, an Orifice Flowmeter included in the straight portion of the liquid line, and 4 valves for controlling the flow. The copper vessel sat on an electric heater inside a steel cylinder, and the whole system was insulated against heat loss. The flowmeter is shown in Fig. 4.13.

A glass-tube, ½ in. i.d., and of a special shape, held the experimental wire, (Fig. 4.14 and Plate IV - II), and was included in the circulating system by short rubber-tube connections. The platinum wires used were C grade, supplied by Messrs Johnson Matthey, 78-83, Hatton Garden, London, E.C.1. Their Temp. Coeff. of Resistance was quoted as 0.0035. The method of fixing the wire to its copper leads and mounting it in the glass-tube is shown in Fig.4.14. The ends of the wire were drawn through axial bores in 3/32 in. brass screws and welded to the outer ends of the latter. These screws were fixed into copper rods (3/16 in. dia.)

APPARATUS FOR CIRCULATING BOILING LIQUID OVER HOT WIRE.

FIG. 4·12.

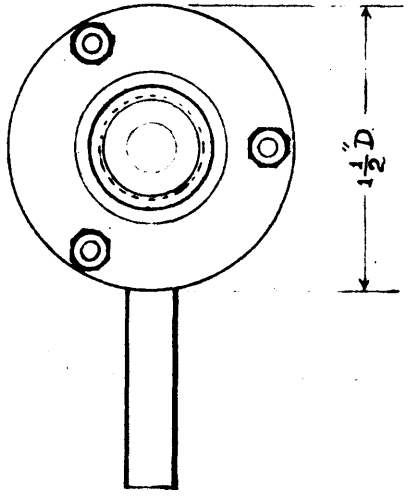
SCALE :- 1:8



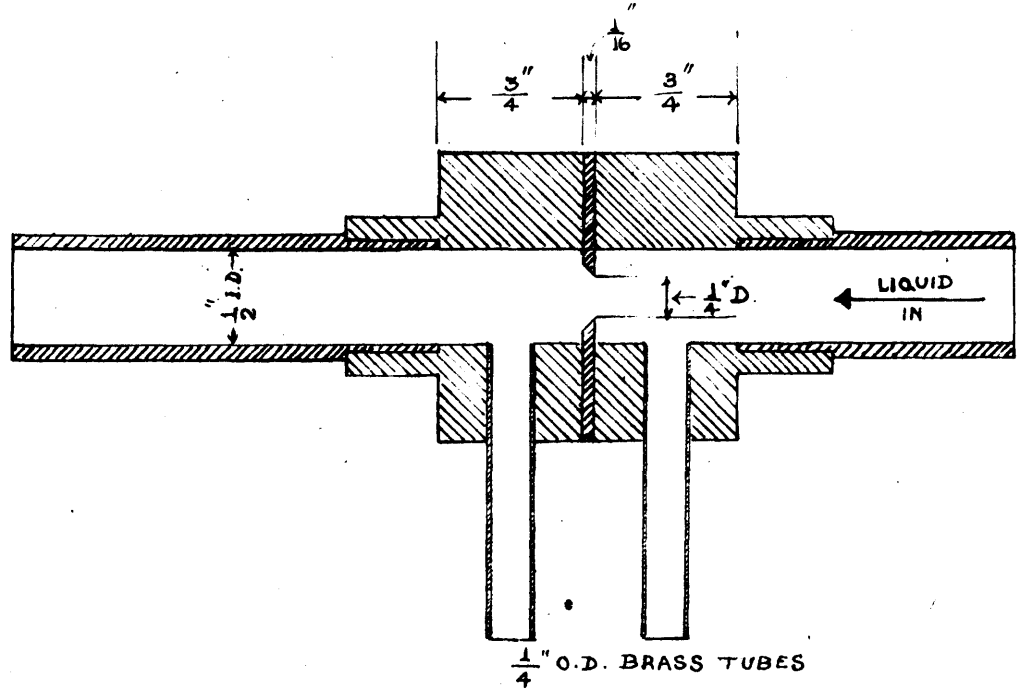
ORIFICE FLOW-METER.

FIG. 4·13.

SCALE: FULL.



END VIEW.



SECTIONED SIDE VIEW.

threaded on the inside to take the screws. Similar screws fixed to the outer ends of the copper rods and carrying nuts provided electrical connection. The Potential Leads were hammer-welded to the element (although spot-welding would have been desirable, no facilities were presently available) at about 1½ in. from the inner end of each brass screw holding the element. The wire was now annealed at red-heat for several minutes by passing current. For 0.02" and 0.01" dia. wires, 0.004 in dia. wire was used as potential lead. For the 0.005 in. dia. wire the potential lead was only 0.002 in. in dia. The wire was now mounted inside the glass-tube by sealing its copper leads to the side-tubes (Fig. 4.14) with cold-setting "Marco" Resin No. 65 O*. The potential leads were taken out through side-tubes which were then sealed. Electrical connection with the potential leads was obtained by fixing a short length of rubber-tubing to the side-tubes and putting some mercury into it. Iron leads connected to the rocking switch of the potentiometer circuit dipped into this mercury.

EXPERIMENTAL PROCEDURE+

The flowmeter was first calibrated for water and ethyl alcohol. The calibration curves are

---

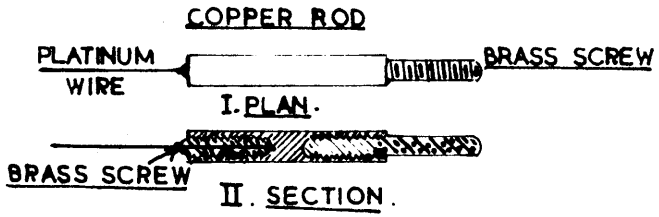
* Supplied by Messrs Scott Bader & Co., Ltd., 109, Kingsway, London, W.C.2.

FIG. 4.14.

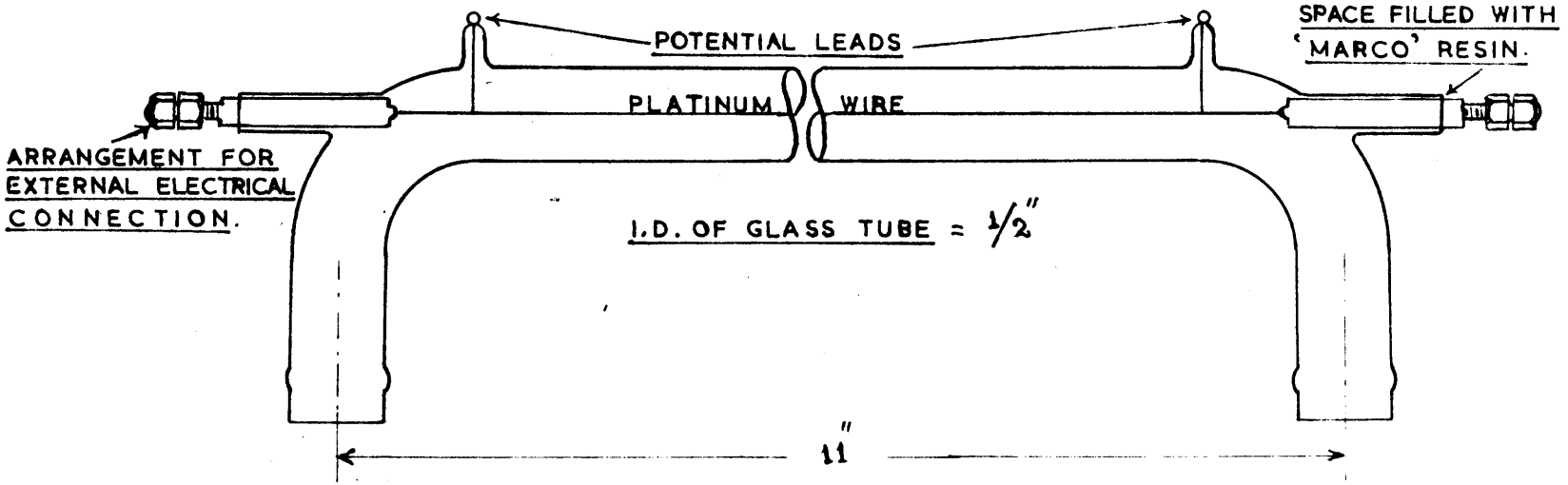
FIXING AND MOUNTING THE PLATINUM WIRE.

SCALE : FULL.

FIXING IT :-



MOUNTING IT :-



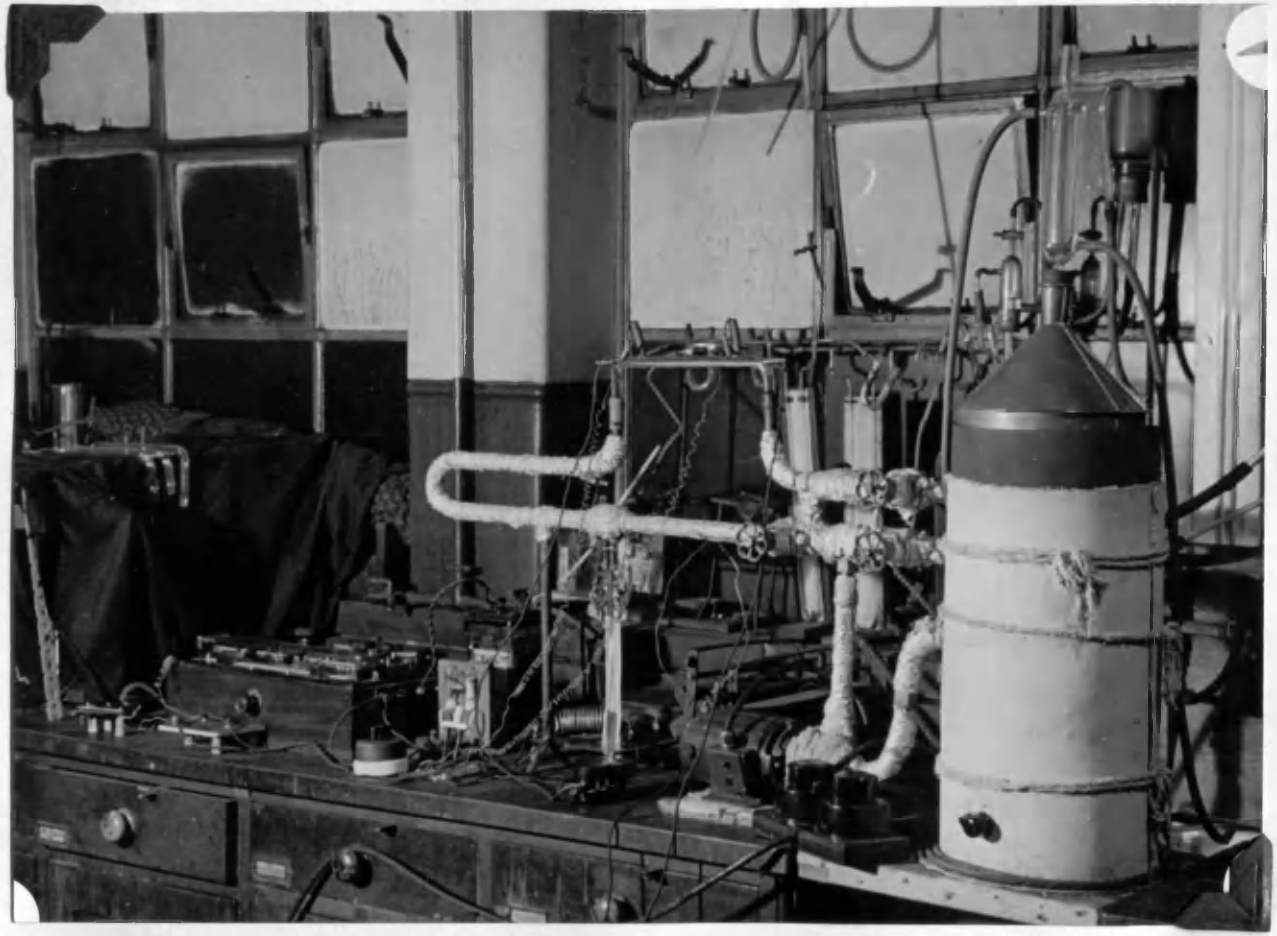
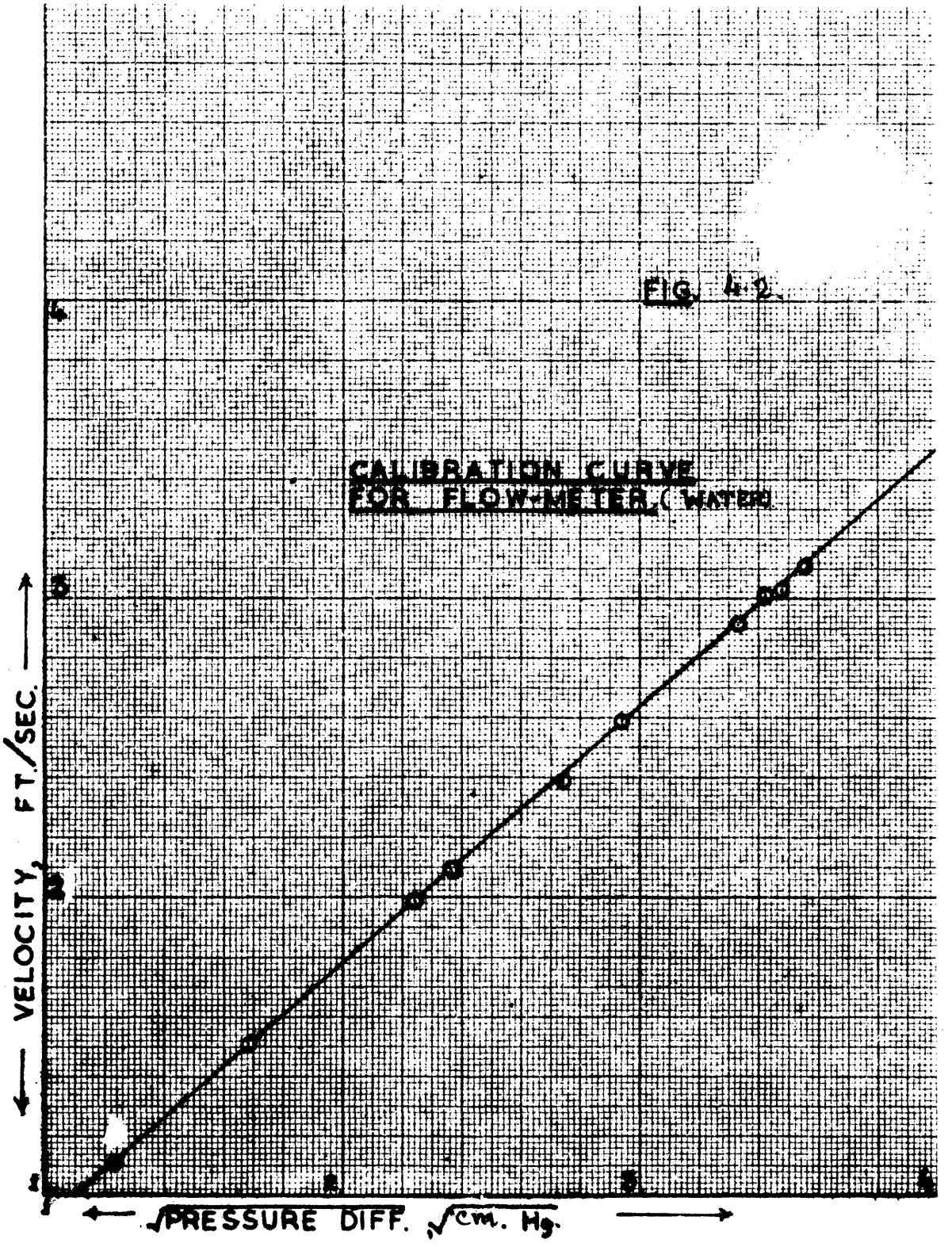


Plate. IV-I. Complete Assembly for studying Boiling over heated platinum wires, with the liquid under forced-circulation.

FIG. 4·2.


CALIBRATION CURVE FOR FLOW-METER (WATER)
VELOCITY, FT./SEC.
√PRESSURE DIFF. √cm. Hg.

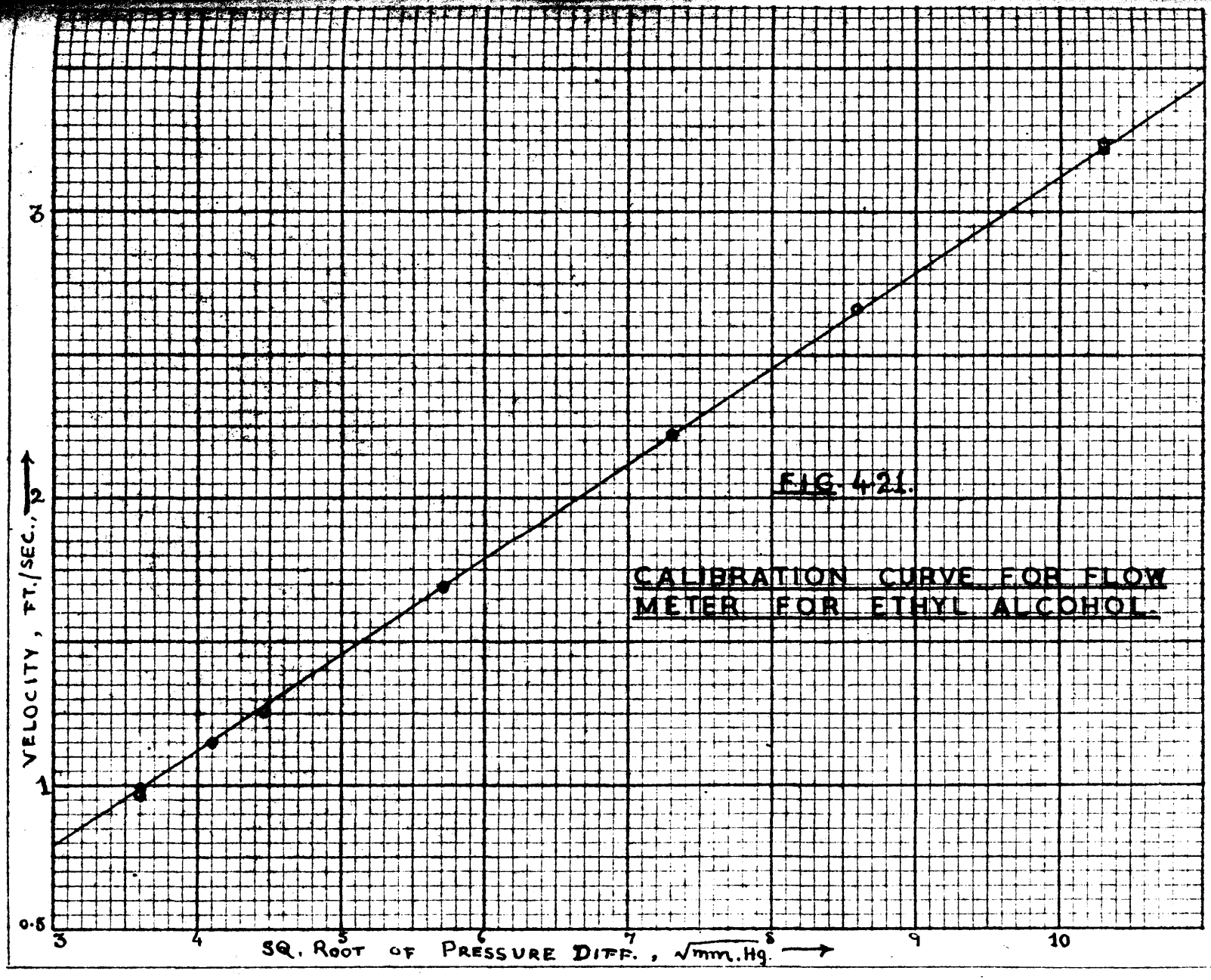


FIG. 421.

CALIBRATION CURVE FOR FLOW METER FOR ETHYL ALCOHOL.

shown in Figs. 4.2 and 4.21, respectively. The wire was now calibrated for its resistance at 0°C and at 100°C by passing a nominal current through it and measuring the voltage drops across the semi-standard and across the potential leads of the wire. The 0.005 in. wire was calibrated at the temperature of boiling 95.6% Et.OH, instead of at 100°C. This wire was not used with water.

The glass tube was now mounted on the circulating system, the circulating pump started, and the liquid made to boil at a steady, moderate, rate. The valves A and B were adjusted to give the desired rate of flow. For measurements in the "Nucleate" region, a small D.C. was now passed through the wire, and potential drops were measured across the semi-standard and across the potential leads, with the potentiometer. The current was then increased by small steps to a maximum and decreased in steps, and a series of voltage and current readings was recorded. With each liquid-wire pair determinations were made at three different liquid velocities of 1 ft/sec., 2 ft/sec., and 2.9 ft/sec., respectively.

Some data were also taken in the "film boiling" region. To induce film boiling on the whole wire without causing its burn out, the following procedure was adopted. To begin with, nucleate boiling was induced. The current was increased to a high value by adjusting the variable resistance,

the boiling still being of the nucleate type. Without making any further alterations, the current was momentarily switched off. On turning the switch on again, film boiling set in over most of the wire and quickly spread over the rest of it. Measurements of potential drops were now begun in the usual way. The current was lowered in steps and readings taken at each step. When the current strength became small, boiling suddenly reverted to the nucleate type without requiring any special manipulation to avoid burn out of the wire. The measurements were confined to the 0.01 in. dia. wire with ethyl alcohol at 2 ft/sec., and 2.9 ft/sec., liquid velocities, respectively.

CALCULATIONS:-

These were made as follows :-

(1) Heat Load per hour, q, = 3.415 E.I.

(2) Area of wire, A, = $\pi D \cdot L$,

where D = Dia.

L = Length.

(3) Resistance of the Wire at Temperature, t,

$$R_t = \frac{E}{I}.$$

(4) Wire temperatures were computed from the following relation:-

$$t_p = \frac{R_t - R_o}{R_{100} - R_o} \times 100.$$

For the 0.005 in. wire calibrated at 78.6°C, for instance, the following relation was used:-

$$t_p = \frac{R_t - R_o}{R_{78.6} - R_o} \times 78.6.$$

For the 0.02 wire a radial correction was applied; the surface tmperature of the wire was obtained from the following relation :-

$$t_s = t_p - \frac{(q/A)\, D}{8\, k}$$

which may be derived by assuming uniform generation of electric heat in the Platinum and constant thermal conductivity. This radial correction amounted to only a few tenths of a per cent in the case of water with the two thinner wires and in the case of all the wires with Et.OH;as temperature measurements were not very precise, this correction was not applied in these cases.

RESULTS :-

These are set out in Tables 4.1 and 4.2. The designation of the series is on the following basis:-

Nos. 1, 2, and 3 - These refer to the liquid velocities of 1, 2, and 2.9 ft/sec., respectively.

A = 0.02 in. wire,

B = 0.01 " "

C = 0.005 in. wire

E = Ethyl Alcohol (95.6% by weight).

Where A, B, and C are unaccompanied with E, they refer to tests on water. Numerical suffixes, 1, 2, etc., refer to repeat tests with the same liquid-wire pair at the same liquid velocity. Thus, series '1 - AE_1' means that the tests on ethyl alcohol with 0.02 in. wire, at a liquid velocity of 1 ft/sec., have been repeated once.

ACCURACY OF MEASUREMENT :-

Since the flowmeter was calibrated with cold liquids, this calibration would not hold closely for the liquids at their boiling points. A further complication was introduced by the fact that the pump tended to suck a mixture of liquid and vapour from the copper vessel and compress it into the tubes. Since the composition of this mixture varied from moment to moment, a pulsating flow was obtained as indicated by the mercury manometer. This pulsating flow caused a consequent unsteady temperature of the platinum wire. This was reflected in the spot of light of the galvanometer, which was seldom steady. It was, therefore, very difficult to obtain precise balance of the potentiometer. This fluctuation must have caused as high an error as ± 10% in temperature measurement at low values of current.

The potentiometer was also not capable of great accuracy. Assuming an error of ± 1% in the measurement of length and dia. of the wire, it is probable that at low values of flux, results may have an error of ± 20%. At the highest values of flux, this error may still be of the order of ± 10%.

OBSERVATIONS ON BOILING

When the current was increased from a very small value upwards, boiling did not set in until a cerain minimum flux was reached. This minimum flux increased with a decrease in the diameter of the wire. It also increased with increasing liquid velocity, although the difference between the values for the two higher velocities was not considerable. Water, for the same wire and liquid velocity, began boiling under a much higher flux than ethyl alcohol. These minimum values of flux at which boiling just commenced, are indicated in the Tables of Results by an asterisk for most of the test series. At the start of boiling only two or three nuclei used to be active, but their number quickly increased with rising flux, and covered the whole wire.

With ethyl alcohol another interesting observation was made. When the flux was gradually increased boiling did not set in until the value of the former became fairly high. Vigorous boiling would then suddenly set in over the whole

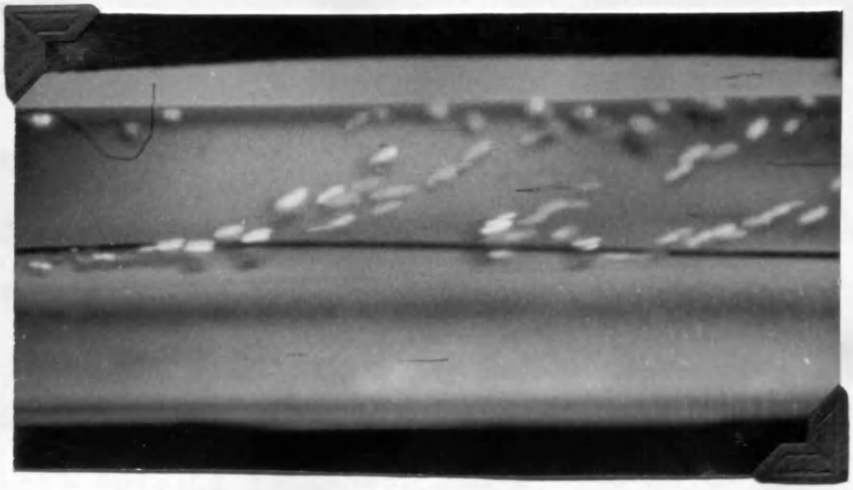


Plate. IV-III. Ethyl Alcohol boiling over 0.01 in. dia. Pt Wire. Flux = 15,000 B.Th.U/hr/sq.ft. Temp. Drop = 25°F. Liquid velocity = 1 ft./sec. Exposure : 1/500 sec.

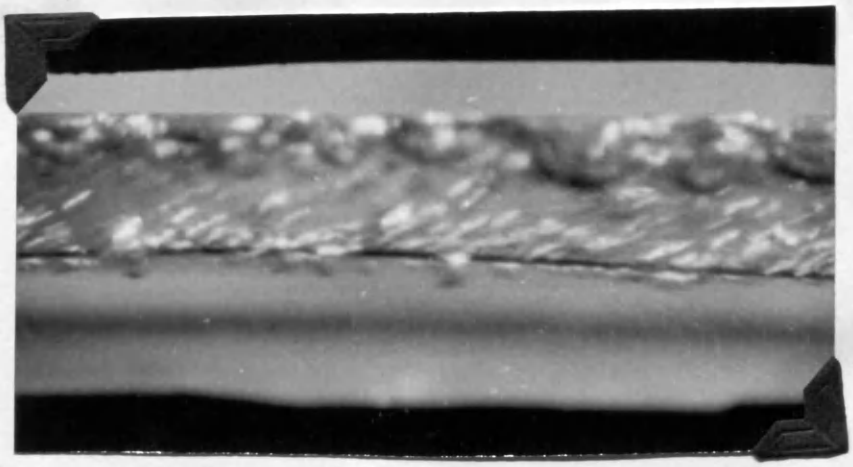


Plate. IV-IV. Ethyl Alcohol boiling over 0.01 in. dia. Pt Wire. Flux = 38,000 B.Th.U/hr/sq.ft. Temp. Drop = 28.5°F. Liquid velocity = 1 ft./sec. Exposure : 1/500 sec.

wire. The flux was increased further, for measurements in the nucleate region, and then gradually decreased. This time the boiling did not cease at that value of flux where it had commenced on going up. It continued down to a flux value much lower than the previous one. This would suggest a marked tendency of ethyl alcohol for superheating. With water it was found that boiling commenced and ceased at practically the same value of flux. The tendency of alchol for superheating was greater with wires of smaller diameter.

The boiling of ethyl alcohol over 0.01 in. dia. wire at a liquid velocity of 1 ft/sec., under fluxes of 15000 B. Th.U./hr/sq.ft., and 38000 B.Th.U/hr/sq.ft., is shown in Plates (IV - III) and (IV-IV), respectively.

.....

TABLE 4.1 (WATER)

Series 1—A

Length of wire = 10.3 in. Test Section = 6.75 in.

Dia. of wire = 0.020 in. Surface Area = 0.002948 sq.ft.

R_{100} = 0.1260 ohms. $R_{100} - R_0$ = 0.0302 ohms.

Liquid velocity = 1ft/sec.

Test No.	E (volts)	I (amps)	R_t (ohms)	Δt (°F.)	Radial Correction (°F)	Corrected Δt °F	q/A	h.
1.	0.3691	2.922	0.1264	2.16	----	2.2	1250	568
2.	0.5100	4.033	0.1265	3.96	----	4.0	2385	596.3
3.	0.6501	5.044	0.1269	5.40	----	5.4	3743	693
4.	0.7634	6.008	0.1271	6.57	----	6.6	5309	805
5.	0.9117	7.140	0.1276	9.72	0.004	9.7	7543	778
6.	1.0104	7.910	0.1278	10.87	0.005	10.9	9260	850
7.	1.1426	8.916	0.1282	13.19	0.06	13.1	11800*	901
8.	1.3967	10.870	0.1285	15.03	0.09	14.9	17580	1180
9.	1.5353	11.920	0.1288	16.74	0.11	16.6	21170	1276
10.	1.6647	12.958	0.1285	15.03	0.12	14.9	25000	1678
11.	1.2685	9.905	0.1281	12.60	0.07	12.5	14560	1166
12.	1.0306	8.182	0.1275	9.09	0.005	9.1	9655	1061
13.	0.7891	6.206	0.1272	7.2	---	7.2	5670	787
14.	0.6411	5.053	0.1269	5.4	---	5.4	3755	696

Series 2 - A. (Liquid velocity - 2 ft/sec.)

1.	0.4130	3.268	0.1264	2.39	--	2.4	1564	651.5
2.	0.7962	6.267	0.1271	6.66	--	6.7	5780	863
3.	1.2240	9.520	0.1286	19.56	0.06	19.5	13500	692.5
4.	1.3685	10.630	0.1288	19.64	0.08	19.6	16840*	860.0
5.	2.0680	15.900	0.1300	23.88	0.18	23.7	38110	1608
6.	2.4750	18.950	0.1306	27.45	0.26	27.2	54300	1996
7.	2.865	21.86	0.1311	30.60	0.34	30.3	72500	2394
8.	3.205	24.30	0.1320	35.76	0.43	35.3	90200	2556

* Minimum Flux value for the commencement of boiling.

T A B L E. 4.1 (Continued)

Wire Dia. = 0.020 in. Length = 9.2 in. Test Section = 6.8 in. Heat Transfer Area = 0.002966 sq.ft. R_{100} = 0.1265 ohms. $R_{100} - R_0$ = 0.0327 ohms.

SERIES. 1-A_1.

(Velocity = 1 ft/sec.)

Test No.	E volts	I amps.	R_t ohms	Δt °F	Radial correction. °F	Corr. Δt °F	$\frac{q}{A}$	h
1.	0.3212	2.523	0.1274	4.96		5.0	927	185.4
2.	0.3239	2.539	0.1276	6.05		6.1	942	154.5
3.	0.4223	3.304	0.1278	7.15	0.008	7.1	1595	224.7
4.	0.4269	3.325	0.1282	9.36	0.008	9.4	1622	172.6
5.	0.6623	5.152	0.1286	11.56	0.02	11.5	3900	339.1
6.	0.6624	5.154	0.1286	11.56	0.02	11.5	3902	339.3
7.	1.0447	8.086	0.1292	14.86	0.048	14.8	9660	652.6
8.	1.0452	8.100	0.1292	14.86	0.048	14.8	9750	658.8
9.	1.2682	9.805	0.1294	15.96	0.07	15.9	14230	893.5
10.	1.2801	9.905	0.1294	15.96	0.07	15.9	14500	912.5
11.	1.7005	13.105	0.1298	18.17	0.13	18.0	25480	1415
12.	1.7024	13.130	0.1298	18.17	0.13	18.0	25560	1420
13.	2.139	16.36	0.1307	23.11	0.20	22.9	40000	1748
14.	2.215	16.93	0.1308	23.68	0.21	23.5	42900	1826

SERIES. 2-A_1.

(Velocity = 2 ft/sec.)

R_{100} = 0.1260 ohms; R_0 = 0.0938 ohms; $R_{100} - R_0$ = 0.0322 ohms

1.	0.4181	3.306	0.1265	2.80		2.8	1592	569.0
2.	0.8058	6.334	0.1272	6.71	0.03	6.7	5880	878.0
3.	1.239	9.650	0.1284	13.42	0.07	13.4	13760	1027.0
4.	1.385	10.775	0.1285	13.98	0.09	13.9	17180	1237
5.	1.700	13.173	0.1290	16.76	0.13	16.6	25780	1553
6.	2.095	16.155	0.1297	20.69	0.20	20.5	39000	1902
7.	2.507	19.26	0.1302	23.48	0.28	23.2	55610	2397
8.	2.866	21.92	0.1308	26.84	0.37	26.5	72380	2732
9.	3.246	25.71	0.1314	30.20	0.47	29.7	92380	3112

T A B L E. 4.1 (Continued)

R_{100} = 0.1265 ohms; R_0 = 0.0941; $R_{100} - R_0$ = =0.0324 ohms. Other details same as on the last page.

SERIES. 3-A.

(Velocity = 2.9 ft/sec.)

Test No.	E volts	I amps.	R_t ohms	Δt °F	Radial Corr. correction °F	Corr. Δt °F	$\frac{q}{A}$	h
1.	1.0551	8.212	0.1285	11.12	0.05	11.1	9980	899.0
2.	1.250	9.655	0.1295	16.66	0.07	16.6	13895	837.0
3.	1.628	12.54	0.1298	18.34	0.12	18.2	23520	1292
4.	2.066	15.86	0.1303	21.10	0.19	20.9	37760	1808
5.	2.496	19.06	0.1310	25.02	0.28	24.7	54780	2219
6.	2.852	21.74	0.1313	26.68	0.36	26.3	71400	2716
7.	3.258	24.78	0.1315	27.80	0.47	27.3	92980	3409
8.	3.679	27.92	0.1318	29.45	0.60	28.9	118350	4098
9.	3.381	25.76	0.1313	26.68	0.51	25.2	100240	3828
10.	2.708	20.70	0.1308	23.90	0.33	23.6	64550	2736
11.	2.024	15.61	0.1297	17.78	0.19	17.6	36370	2067
12.	1.462	11.32	0.1292	15.00	0.10	14.9	19070	1280
13.	1.031	8.025	0.1285	11.12	0.05	11.1	9530	859.0

SERIES. 1-B.

Wire Dia.= 0.010 in. Length = 10.3 in. Test Section = 6.84 in. Heat Transfer Area = 0.001492 sq.ft. R_{100} = 0.5290 ohms. $R_{100} - R_0$ = 0.1365 ohms. (Velocity ---- 1ft/sec.)

1.	0.5694	1.075	0.5300	--	--	1.3	1405	1081
2.	0.9023	1.702	0.5305	--	--	2.0	3515	1757
3.	1.626	3.045	0.5345	--	--	7.3	11340	1555
4.	1.643	3.082	0.5331	--	--	5.4	11590	2147
5.	2.181	4.050	0.5386	--	--	12.7	20210	1592
6.	2.288	4.246	0.5391	--	--	13.3	22250	1674
7.	2.738	5.050	0.5420	--	--	17.2	31640	1841
8.	2.861	5.266	0.5435	--	--	19.1	34500	1806
9.	3.231	5.934	0.5450	--	--	21.1	43900	2080
10.	3.413	6.260	0.5453	--	--	21.5	48900	2274

T A B L E. 4.1.(Continued)

SERIES.2-B.

(Velocity = 2 ft/sec.)

Test No.	E volts	I amps.	R_t ohms	Δt °F	$\frac{q}{A}$	h
1.	1.236	2.330	0.5315	3.3	6590	1996
2.	1.612	3.023	0.5333	5.7	11160	1958
3.	2.274	4.236	0.5372	10.8	22050	2044
4.	2.340	4.351	0.5380	11.9	23300	1960
5.	2.699	5.007	0.5388	12.9	26860	2082
6.	2.817	5.230	0.5390	13.2	33740	2557
7.	3.238	5.986	0.5410	15.8	44400	2804
8.	3.565	6.590	0.5412	16.1	53800	3340
9.	3.573	6.600	0.5415	16.5	54000	3274
10.	4.108	7.556	0.5440	19.8	71000	3588

SERIES: 3-B
(Velocity = 2.9 ft/sec.)

1.	1.030	1.942	0.5308	2.4	4576	1908
2.	1.213	2.285	0.5310	2.6	6345	2443
3.	1.584	2.980	0.5320	4.0	10800	2700
4.	1.599	3.003	0.5328	5.0	10990	2198
5.	2.009	3.772	0.5330	5.3	17350	3273
6.	2.676	4.985	0.5370	10.6	30530	2880
7.	2.717	5.059	0.5372	10.8	31480	2916
8.	3.223	5.981	0.5390	13.2	44150	3345
9.	3.519	6.520	0.5397	14.1	52500	3725
10.	3.688	6.823	0.5410	15.8	57610	3650
11.	3.740	6.910	0.5415	16.5	59130	3584
12.	4.398	8.038	0.5470	23.8	80950	3402
13.	4.401	8.060	0.5463	22.8	81200	3560

T A B L E. 4.2.

ETHYL ALCOHOL.

Wire Dia. = 0.020 in. Length = 9.2 in. Test Section = 6.8 in. Heat Transfer Area = 0.002966 sq.ft.
R_{100} = 0.1265 ohms. $R_{100} - R_0$ = 0.0324 ohms.
Boiling Point of Ethyl Alcohol = 78.6 °C.

SERIES: 1-AE.

(Velocity = 1 ft/sec.)

Test No.	E volts.	I amps.	R_t ohms.	Δt °F	q/A	h
1.	0.2453	2.034	0.1206	5.8	574	99.0
2.	0.3879	3.201	0.1212	9.1	1430	157.0
3.	0.6494	5.321	0.1221	13.8	3997	288.3
4.	0.7385	6.032	0.1223	15.3	5132	335.5
5.	1.0075	8.190	0.1231	19.7	9505	483.0
6.	1.021	8.262	0.1236	22.4	9720	434.0
7.	1.142	9.225	0.1238	23.6	12140	514.3
8.	1.148	9.275	0.1238	23.6	12270	520.0
9.	1.561	12.560	0.1243	26.3	22550	866.0
10.	1.564	12.595	0.1242	25.7	22680	882.0
11.	1.560	12.560	0.1243	26.3	22550	866.0

SERIES: 2-AE. (Velocity = 2 ft/sec.)

1.	0.3448	2.852	0.1209	7.4	1133	153.2
2.	0.3598	2.976	0.1210	7.9	1192	150.9
3.	0.6263	5.150	0.1216	11.2	3713	331.7
4.	0.7360	6.035	0.1220	13.5	5116	379.5
5.	0.7425	6.090	0.1220	13.5	5209	386.0
6.	0.7560	6.170	0.1226	16.9	5370	317.7
7.	1.0075	8.195	0.1230	19.1	9390	492.0
8.	1.0934	8.820	0.1241	25.2	11100	440.4
9.	1.0967	8.830	0.1242	25.8	11150	432.0
10.	1.2810	10.345	0.1239	24.1	15260	633.0
11.	1.5735	12.630	0.1246	28.0	22930	819.0
12.	1.6322	13.130	0.1244	26.8	24700	921.0
13.	1.6334	13.130	0.1245	27.5	24710	898.5
14.	1.9277	15.470	0.1248	29.1	34140	1180.0

T A B L E. 4.2 (Continued)

SERIES: 3-AE. (Velocity = 2.9 ft/sec.)

Test No.	E volts	I amps.	R_t ohms	Δt °F	q/A	h
1.	0.3438	2.845	0.1209	7.4	1127	152.4
2.	0.4535	3.745	0.1212	9.1	1957	215.0
3.	0.6238	5.131	0.1216	11.2	3685	329.0
4.	0.7431	6.105	0.1218	13.2	5221	395.6
5.	0.9742	7.962	0.1224	15.8	8930	565.4
6.	0.9863	8.010	0.1232	20.2	9095	450.0
7.	1.1367	9.180	0.1239	24.1	12020	498.8
8.	1.4268	11.535	0.1238	23.6	18965	803.5
9.	1.5138	12.195	0.1242	25.8	21260	824.0
10.	1.846	14.815	0.1247	28.5	31460	1104.0
11.	1.946	15.590	0.1249	29.7	34910	1176.0
12.	2.145	17.130	0.1253	31.8	42300	1330.0

SERIES: 1-BE. (Velocity = 1 ft/sec)

Wire Dia. = 0.010 in. Length = 10.3 in. Test Section = 6.84 in. Heat Transfer Area = 0.001492 sq.ft. R_{100} = 0.5290 ohms. $R_{100} - R_0$ = 0.1365 ohms.

1.	0.4725	0.9390	0.5030	4.3	1006	234.0
2.	0.4835	0.9626	0.5023	3.4	1065	313.5
3.	0.6726	1.3355	0.5037	5.2	2055	395.3
4.	0.9985	1.968	0.5072	9.9	4493	454.0
5.	1.0831	2.132	0.5082	11.2	5284	467.4
6.	1.4205	2.769	0.5135	18.2	9000	495.0
7.	1.6153	3.120	0.5180	24.1	11540	479.3
8.	2.1512	4.133	0.5205	27.4	20350	743.3
9.	2.2245	4.276	0.5203	27.2	21750	799.5
10.	2.992	5.740	0.5215	28.7	39330	1370.0
11.	2.994	5.746	0.5215	28.7	39400	1373.0
12.	3.086	5.920	0.5220	29.3	41780	1426.0

T A B L E. 4.2 (Continued)

SERIES: 2-BE. (Velocity - 2 ft/sec.)

Test No.	E volts	I amps.	R_t ohms	Δt F.	q/A	h
1.	0.7636	1.508	0.5061	8.46	2634	310.0
2.	0.7638	1.508	0.5063	8.7	2635	303.0
3.	1.3827	2.699	0.5126	17.0	8535	502.2
4.	1.3844	2.703	0.5121	16.3	8565	525.5
5.	1.0584	2.075	0.5100	13.7	5023	367.0
6.	1.0596	2.076	0.5100	13.7	5032	367.6
7.	1.8057	3.508	0.5150	20.2	14500	715.5
8.	1.8078	3.510	0.5153	20.5	14525	708.5
9.	2.522	4.842	0.5210	28.1	27970	996.0
10.	2.536	4.911	0.5165	22.1	28500	1290.0
11.	2.756	5.296	0.5202	27.0	33420	1238.0
12.	2.867	5.500	0.5215	27.2	36100	1328.0
13.	2.876	5.510	0.5220	29.5	36260	1230.0
14.	3.080	5.875	0.5240	32.2	41400	1286.0
15.	3.082	5.890	0.5232	31.1	41550	1337.0

SERIES: 3-BE. (Vel.- 2.9 ft/sec.)

1.	0.6437	1.274	0.5050	7.0	1878	268.3
2.	0.6466	1.278	0.5059	8.2	1892	230.7
3.	0.9541	1.880	0.5075	10.3	4105	398.7
4.	1.1392	2.245	0.5076	10.4	5854	563.0
5.	1.5711	3.070	0.5118	15.9	11030	693.7
6.	1.5717	3.071	0.5121	16.4	11040	673.3
7.	1.5720	3.075	0.5111	15.1	11050	732.0
8.	1.8142	3.530	0.5141	19.0	14660	772.0
9.	2.072	4.010	0.5167	22.4	19030	850.0
10.	2.747	5.270	0.5211	28.2	33110	1174.0
11.	2.755	5.275	0.5222	29.6	33250	1123.0
12.	3.088	5.911	0.5222	29.6	41760	1411.0
13.	3.203	6.142	0.5215	28.8	45000	1563.0

T A B L E. 4.2. (Continued)

SERIES 1 - BE_1. (Velocity = 1 ft/sec.)

Test No.	E volts	I amps.	R_t ohms	Δt ^oF	$\frac{q}{A}$	h
1.	0.5175	1.034	0.5010	6.7	1230	183.6
2.	0.7290	1.455	0.5010	6.7	2400	364.0
3.	1.490	2.901	0.5137	23.6	9960	422.1
4.	2.122	4.093	0.5188	30.4	20010	658.5
5.	2.804	5.363	0.5229	36.0	33400	928.0
6.	3.408	6.524	0.5224	35.2	51300	1458.0
7.	1.165	2.294	0.5078	15.7	5870	374.0
8.	0.9883	1.953	0.5053	12.4	4430	357.4
9.	0.3192	0.6412	0.4979	2.5	471	188.5

SERIES 1-BE_2. (Velocity = 1 ft/sec.)

$R_{78.6}$ = 0.4960 ohms; $R_{78.6} - R_0$ = 0.1035 ohms.

Test No.	E volts	I amps.	R_t ohms	Δt ^oF	$\frac{q}{A}$	h
1.	2.709	5.056	0.5358	53.1	31500	594.2
2.	2.093	4.043	0.5175	27.7	19500	704.5
3.	1.543	3.043	0.5071	14.8	10880	731.0
4.	1.301	2.550	0.5103	19.1	7640	400.0
5.	0.9576	1.902	0.5034	9.9	4190	423.4
6.	0.5130	1.025	0.5006	6.1	1211	198.6
7.	1.803	3.486	0.5168	27.8	14460	520.0
8.	2.992	5.608	0.5461	66.9	38650	578.0

T A B L E. 4.2. (Continued)

SERIES 2-BE_1. (Velocity = 2 ft/sec.)

$R_{78.6}$ = 0.4960 ohms; $R_{78.6} - R_0$ = 0.1035 ohms.

Test No.	E volts	I amps.	R_t ohms	Δt ^oF	$\frac{q}{A}$	h
1.	0.5011	1.002	0.5000	5.4	1156	214.2
2.	0.6309	1.259	0.5012	7.0	1824	260.5
3.	1.365	2.681	0.5091	17.5	8428	482.0
4.	1.735	3.388	0.5122	21.6	13540	627.0
5.	2.172	4.225	0.5141	24.2	21130	873.0
6.	2.669	5.130	0.5195	31.4	31590	1007.0
7.	2.642	5.082	0.5199	31.9	30910	969.0
8.	2.767	5.328	0.5203	32.3	33950	1051.0
9.	3.007	5.771	0.5212	33.6	39960	1190.0
10.	3.229	6.172	0.5234	36.5	45910	1258.0
11.	3.136	5.969	0.5254	39.3	43110	1098.0
12.	2.986	4.972	0.6006	136.9	34190	250.0
13.	3.299	5.250	0.6284	177.0	39890	225.5
14.	3.923	5.246	0.7480	337.0	47410	140.7
15.	3.995	5.288	0.7554	346.0	48650	140.7
16.	4.305	5.495	0.7834	384.0	54490	141.8
17.	4.635	5.705	0.8127	424.0	60890	143.6
18.	5.023	5.969	0.8416	461.0	69050	149.8
19.	5.128	5.994	0.8549	480.0	70730	147.4
20.	5.352	6.116	0.8750	506.0	75390	148.9
21.	5.509	6.210	0.8872	523.0	78790	150.7
22.	5.821	6.324	0.9204	566.0	84780	149.8
23.	6.063	6.464	0.9383	591.0	90240	152.8
24.	6.362	6.591	0.9654	614.0	96450	157.2
25.	6.266	6.525	0.9603	620.0	94170	152.0
26.	6.369	6.600	0.9651	627.0	96810	154.5

SERIES 3-BE_1. (Velocity -20 ft/sec.)

1.	0.2432	0.4888	0.4976	2.1	274	130.4
2.	0.5254	1.051	0.5003	5.7	1273	223.3
3.	0.8429	1.679	0.5021	8.2	3259	395.5
4.	0.7591	1.502	0.5056	12.8	2625	205.1
5.	1.223	2.416	0.5058	13.1	6805	520.0
6.	1.503	2.953	0.5088	17.1	10220	597.7

T A B L E. 4.2. (Continued)

SERIES 3-BE_1. (Continued)

Test No.	E volts	I amps.	R_t ohms	Δt_o F	$\frac{q}{A}$	h
7.	2.191	4.245	0.5160	26.7	21420	802
8.	2.596	4.998	0.5194	31.3	29880	995
9.	3.130	6.036	0.5187	30.3	43510	1436
10.	3.417	6.582	0.5192	31.0	51780	1670
11.	4.381	5.559	0.7881	390.0	56100	143.8
12.	5.102	5.974	0.8541	478.0	70210	146.9
13.	5.670	6.336	0.8950	538.0	82730	155.4
14.	6.156	6.510	0.9456	561.0	92300	164.6
15.	6.841	6.969	0.9815	649.0	109800	169.2
16.	7.466	7.466	1.017	696.0	126200	181.4

SERIES 1-CE. (Velocity - 1 ft/sec.)

Wire dia. = 0.005 in.; Length = 9.75 in.; Test Section = 6.8 in.; Heat Transfer Area = 0.000741 sq. ft.
$R_{78.6}$ = 1.940 ohms; $R_{78.6} - R_0$ = 0.414 ohms.

1.	1.1357	0.5827	1.949	3.1	3046	985
2.	1.9635	0.9935	1.977	12.7	8980	707
3.	1.9162	0.9700	1.976	12.3	8565	697
4.	2.6683	1.3335	2.001	20.8	16400	789
5.	2.7913	1.3915	2.006	22.6	17880	791
6.	2.1137	1.0625	1.990	17.1	10340	605
7.	2.9372	1.455	2.019	27.0	19710	730
8.	2.8925	1.436	2.013	24.9	19160	770
9.	3.9923	1.963	2.035	32.5	36130	1112
10.	4.0045	1.957	2.047	36.3	36120	995
11.	3.9300	1.924	2.042	34.8	34820	1001
12.	5.0185	2.457	2.043	35.2	56800	1612
13.	5.8456	2.835	2.062	41.7	76380	1832
14.	5.8532	2.839	2.063	42.0	76600	1824
15.	5.6327	2.746	2.052	38.3	71300	1863

T A B L E. 4.2. (Continued)

SERIES 2-CE. (Velocity - 2 ft/sec.)

Test No.	E volts	I amps.	R_t ohms	Δt ^oF	q/A	h
1.	1.0548	0.5402	1.954	4.8	2625	547
2.	1.5750	0.8035	1.960	6.9	7255	1052
3.	1.9106	0.9690	1.973	11.3	8532	755
4.	2.7686	1.3900	1.992	17.8	17720	995
5.	3.0999	1.5395	2.014	25.3	21980	869
6.	3.7263	1.8475	2.017	26.3	31710	1206
7.	3.9786	1.9560	2.035	32.5	35850	1104
8.	5.0884	2.4800	2.052	38.3	58100	1518
9.	5.1143	2.5015	2.044	35.5	58970	1660
10.	5.8684	2.847	2.061	41.3	77020	1866
11.	5.9038	2.865	2.061	41.3	78000	1889

SERIES 3-CE. (Velocity - 2.9 ft/sec.)

1.	0.8278	0.4236	1.956	5.4	1616	299.4
2.	0.8347	0.4276	1.953	4.4	1646	379.1
3.	0.9246	0.4735	1.954	4.8	2018	420.4
4.	0.9259	0.4744	1.953	4.4	2025	460.3
5.	1.8236	0.9275	1.966	8.9	7800	876
6.	1.8336	0.9310	1.970	10.3	7870	764
7.	2.8992	1.4542	1.993	18.1	19440	1074
8.	3.2443	1.6160	2.007	22.9	24180	1056
9.	3.9551	1.9520	2.027	29.7	35560	1199
10.	3.9756	1.9510	2.033	31.8	35750	1124
11.	5.0155	2.4585	2.041	34.5	56800	1648
12.	5.0322	2.4650	2.042	34.8	57130	1644
13.	5.1234	2.5035	2.047	36.6	59100	1614
14.	5.7939	2.810	2.061	41.3	75000	1816

T A B L E. 4.2. (Continued)

SERIES 1-CE_1. (Velocity - 1 ft/sec.)

Test No.	E volts	I amps.	R_t ohms	Δt_o F	q/A	h
1.	0.9720	0.4980	1.952	4.1	2230	544
2.	2.145	1.080	1.985	15.4	10620	690
3.	3.125	1.540	2.029	30.4	22160	729
4.	4.009	1.952	2.054	39.0	36030	924
5.	5.176	2.510	2.062	41.7	59820	1435
6.	5.845	2.833	2.063	42.0	76260	1815
7.	5.129	2.500	2.052	38.3	59050	1543
8.	4.265	2.085	2.045	35.9	40960	1141
9.	2.460	1.231	1.997	19.5	13940	715

SERIES 2-CE_1. (Velocity - 2 ft/sec.)

1.	2.015	1.021	1.972	10.9	9469	868
2.	3.967	1.956	2.029	30.4	35720	1176
3.	5.165	2.522	2.048	36.9	59940	1624
4.	5.887	2.866	2.054	39.0	77660	1992
5.	5.006	2.441	2.051	37.9	56240	1484
6.	3.962	1.945	2.036	32.8	35460	1082
7.	2.747	1.375	1.998	19.8	17390	879
8.	3.781	1.864	2.028	30.1	32450	1079
9.	2.693	1.348	1.996	19.1	16710	875
10.	1.311	0.6673	1.964	8.2	4026	491

SERIES 3-CE_1. (Velocity 2.9 ft/sec.)

1.	1.052	0.5456	1.928	4.1	2642	644.5
2.	2.093	1.059	1.976	12.3	10210	830
3.	3.009	1.504	2.001	20.8	20830	1002
4.	4.422	2.161	2.046	36.2	43980	1214
5.	6.179	3.014	2.049	37.3	85740	2286
6.	4.983	2.436	2.046	36.2	55890	1544
7.	3.331	1.663	2.002	21.2	25510	1204
8.	1.963	0.9915	1.980	13.7	8962	654.6
9.	0.5680	0.2894	1.263	7.9	4927	624.0

FIG 4.1. FLUX VS. TEMP DROP.
EFFECT OF CONTAMINATION
AND NATURE OF LIQUID
WIRE DIA. = 0.02 INCH.
VELOCITY = 1 FT/SEC.
CLEAN (WATER)
CONTAMINATED (WATER)
CLEAN (ETHANOL)
FLUX x10^-3, B.THU/HR/SQ. FT.
TEMP. DROP, °F

FIG 4.2. EFFECT OF VELOCITY.
VELOCITY, FT/SEC.
1
2
3
WATER
ETHANOL
ETHYL ALCOHOL
FLUX x10^-3, B.THU/HR/SQ. FT.
TEMP. DROP, °F

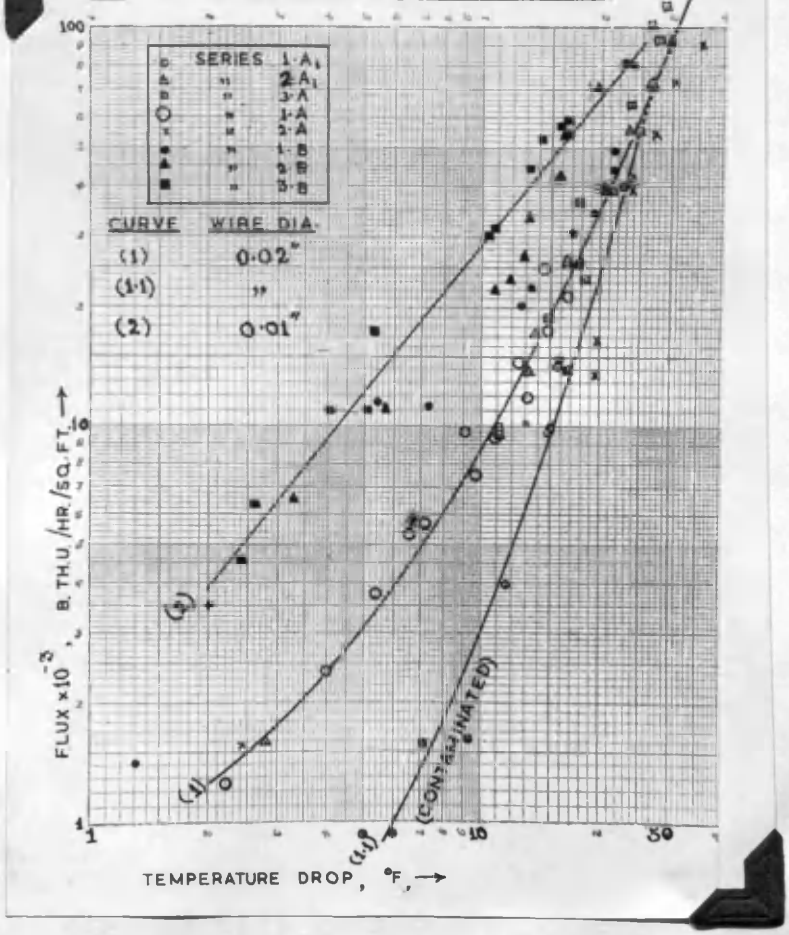
DISCUSSION OF RESULTS

In order to find the effect of various variables on the relationship between heat-flux and temperature drop, the results were plotted on log-log paper in several ways. The curves in Fig. 4.1 were drawn for the 0.02" Dia. wire for 1 ft/sec. velocity for the two liquids. For water, results obtained in two different series were used, and the points were found to lie on two different curves. It is very probable that the wire which had been lying aside for some time before the repeat test was made, became contaminated somehow and, therefore, gave less flux for the same temp. drop. This result agrees qualitatively with the observations of McAdams et al[6] who found that contamination of the wire surface shifted the curve to the right.

The curve for ethyl alcohol with clean wire is still more to the right than the curve for the contaminated wire with water, showing that under similar conditions water gives a much higher flux than ethyl alcohol.

With any given liquid-wire pair, velocity of the liquid parallel to the wire does not seem to have had any considerable effect on the relative positions of the curves for the same liquid (Fig. 4.2, for 0.01" Dia. wire). For water with

FIG. 4·11. FLUX VS. TEMP. DROP FOR WATER.



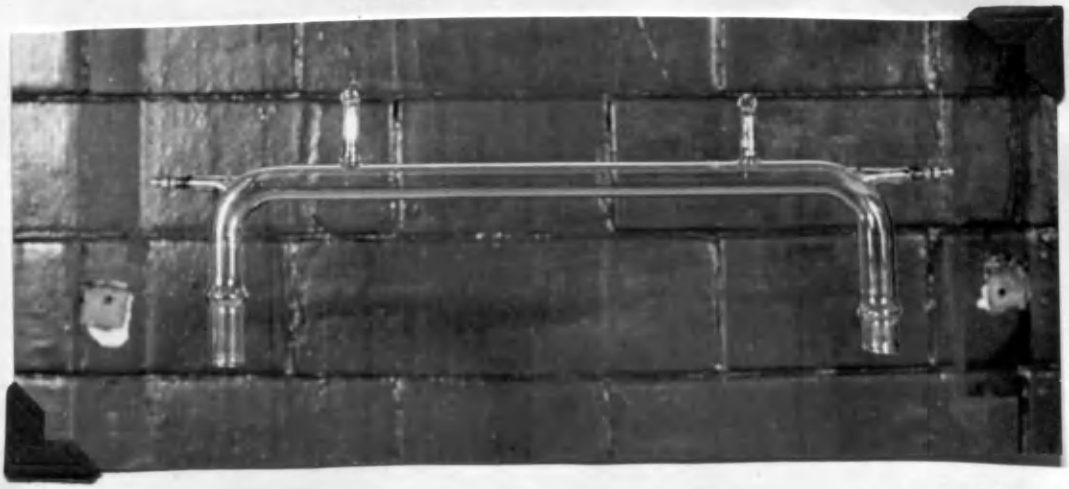
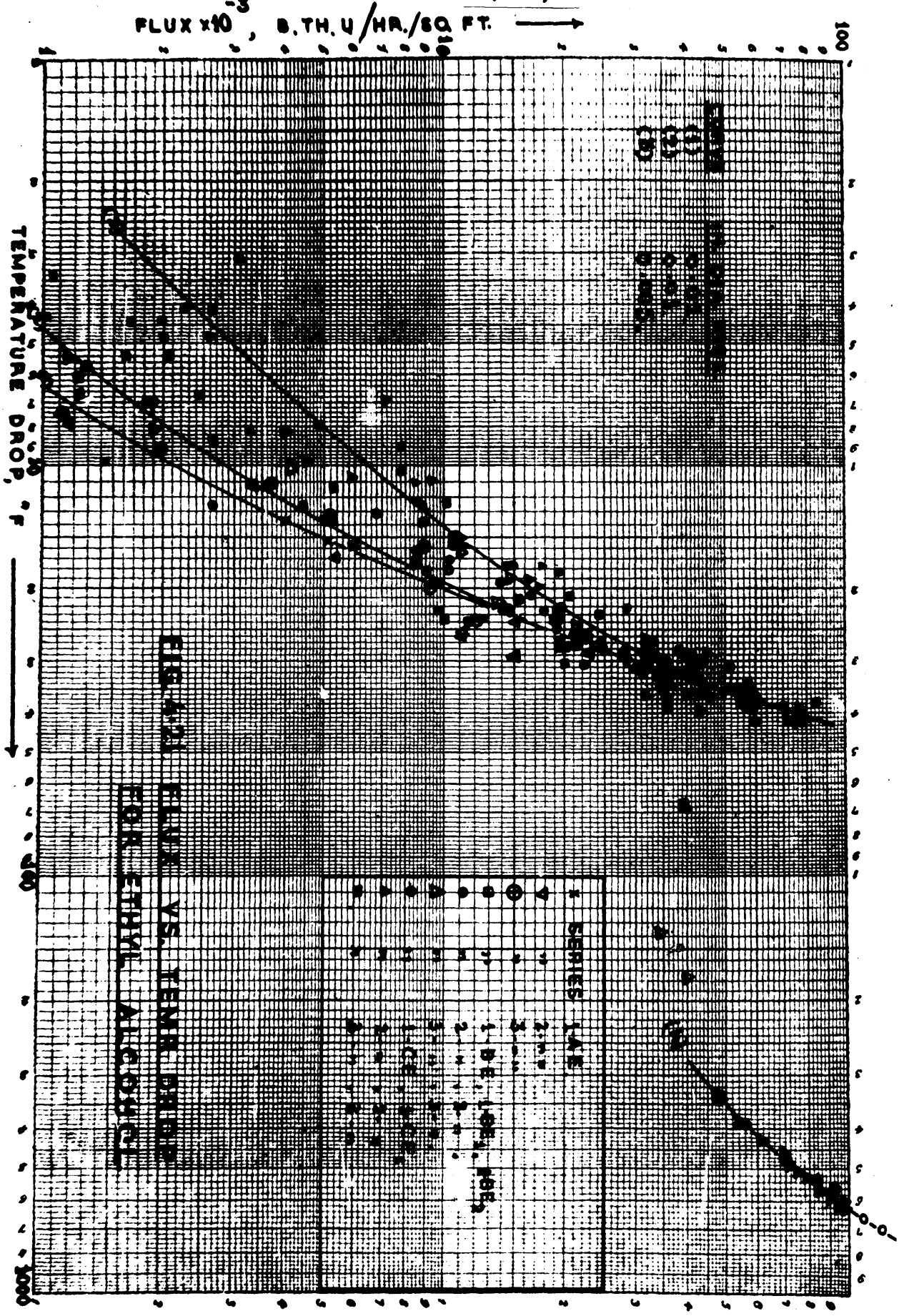


Plate. IV-II. Glass-Tube with Platinum Wire.

the 0.01" dia. wire, the curves for the higher velocities have a slight tendency to be shifted to the left, whereas for ethyl alcohol the effect of velocity, for this same wire, is almost inappreciable, although three curves have been drawn for the points corresponding to the three velocities. At low and high values of Δt, the curves for each liquid have a tendency to merge into one another regardless of velocity. Thus, for water, the curves appear to fall into one for Δt below 5° F and above 25°F. For ethyl alcohol these limits appear to be 15°F and 25°F.

All the results for each liquid were now set out on a separate graph-paper. Figs. 4.11 and 4.21, show the results on water and ethyl alcohol respectively. It will be seen that upto a temp. drop of about 25°F, the curve corresponding to a smaller dia. of wire is situated more to the left. Above Δt of about 25°F, however, all the curves for a particular liquid, approach oneanother, regardless of liquid velocity and wire diameter. In the range of nucleate boiling, this merging into one another of the curves for the different wires, is very distinct in the case of ethyl alcohol. Thus, so far as the effect of wire dia. is concerned, the present results agree closely with those of McAdams et al.[6]

In the range of Film boiling, the points for two different velocities for the same liquid-wire pair lie close-


FLUX x10⁻³, B.TH.U/HR./SQ.FT.
TEMPERATURE DROP, °F
FIG. 121. FILM TEMPERATURE DROP VS. FLUX FOR ETHYL ALCOHOL
SERIES I-VI

ly on the same curve. Three points for ethyl alcohol lie between the curves for true film boiling and nucleate boiling. Their irregular disposition may be due to errors in measurement which was unavoidable considering the irregular boiling that characterises this region.

The nature of the curve in the range of film boiling, and for high values of temperature drop in the range of nucleate boiling, is the same as generally accepted. However, at low values of temp. drop well within the nucleate range, the curves are somewhat more to the left than those obtained by McAdams et al[6]. These authors found that the flux in this region was of the same order as that for simple heating of fluids by natural convection. Obviously, the forced-circulation of the liquid in the present investigations, markedly raised the flux in this region. In agreement with the observations of these authors, the wire diameter seems to have had considerable effect on flux for values of temperature drop below about 25°F, the flux rising with decreasing wire dia. For the same wire, the curves for water are situated higher than those for ethyl alcohol.

The superheating observed here corresponds to the superheating of liquids in a vertical tube evaporator. With the liquid moving at a fast rate, the friction head seems to prevent it from boiling below a certain minimum flux (corres-

ponding to which, therefore, there is a minimum temp. drop). McAdams et al[6] observed that at low values of temp. drop, bubbles formed only on the surface of the pool of water and not on the wire. In the present case this action might have been augmented by the effect of friction head, with the result that the minimum values of temp. drop for the formation of visible bubbles on the surface of the wire ranged from 10°F to 25°F, depending upon the nature of the liquid, its velocity and the diameter of the wire.

.....

C H A P T E R. V.

SOME PHYSICAL PROPERTIES OF ETHYL ALCOHOL AND TOLUENE USED IN THE PREVIOUS CHAPTERS.

CHAPTER V.

The present chapter deals with the determination of some of the physical properties of the liquids used in the tests in the previous chapters.

LATENT HEATS OF VAPORISATION OF ETHYL ALCOHOL AND TOLUENE.

The work on heat transfer to boiling toluene and 95.6% ethyl alcohol necessitated a knowledge of their latent heats of vaporisation over a range of low pressures. The available data on ethyl alcohol were invariably for the pure liquid[62,64] . In the case of toluene no data were available for its latent heat at low pressures.

To determine this experimentally, therefore, a condensation type of apparatus was designed and was found to be unsatisfactory. Other experimenters, using a calorimeter to measure the heat evolved during condensation or absorbed during evaporation, had also obtained disconcordant results. Search was then made for a more reliable method. Marshall and Ramsay[63] using an electrical apparatus compared the heats of evaporation of two liquids, one known and the other unknown. The apparatus used by

Tyrer[61], on the one hand, and by Fiock, Ginnings and Holton[64], on the other, were too elaborate. Consequently, it was decided to adopt J.C.Brown's[62] apparatus to the present use. With this electrical type apparatus fairly satisfactory results have been obtained.

A. THE CONDENSATION TYPE APPARATUS.

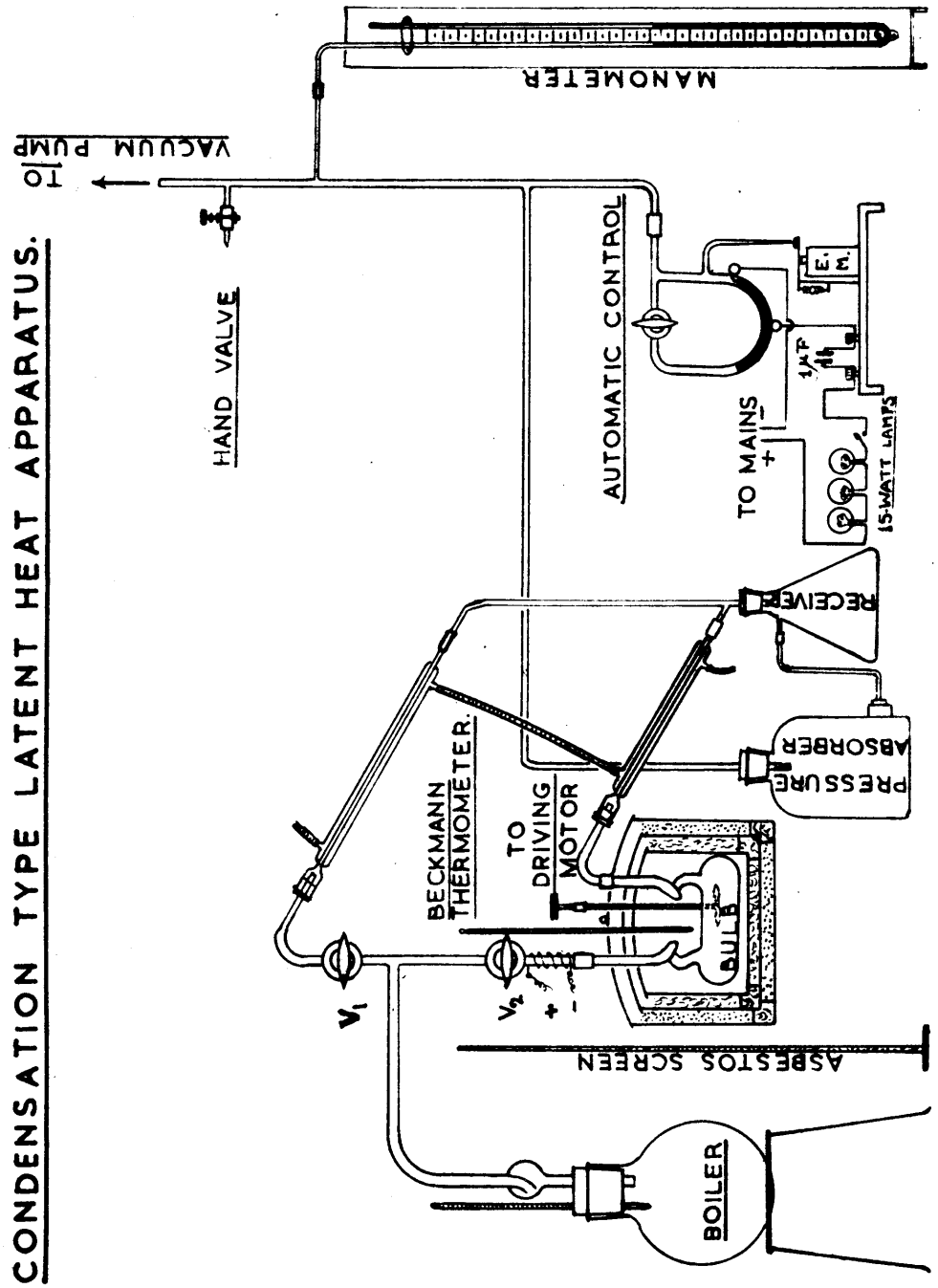
This is shown in Fig.5.1. The calorimeter consisted of three polished aluminium vessels sitting one inside the other, the space between the innermost and the middle one being filled with asbestos wool and that between the middle and the outermost ones with cork powder. The outermost vessel was covered with thick felt. The condensation glass bulb was about 120c.c. in capacity. The calorimeter liquid was thoroughly stirred by a motor-driven stirrer and temperatures were read by a Beckmann thermometer. The vapours from the boiler could either be made to bye-pass the calorimeter, by manipulationg the stop-cocks, V_1 and V_2 , or else they could be led into the condensation bulb. To prevent condensation of vapours before entering the calorimeter, a coil of electrically heated wire was placed round the inlet tube.

PRESSURE CONTROL:-

The pressure in the system was maintained by means of a vacuum pump connected to it through pressure regulating devices. The pressure was primarily controlled by

FIG. 5·1

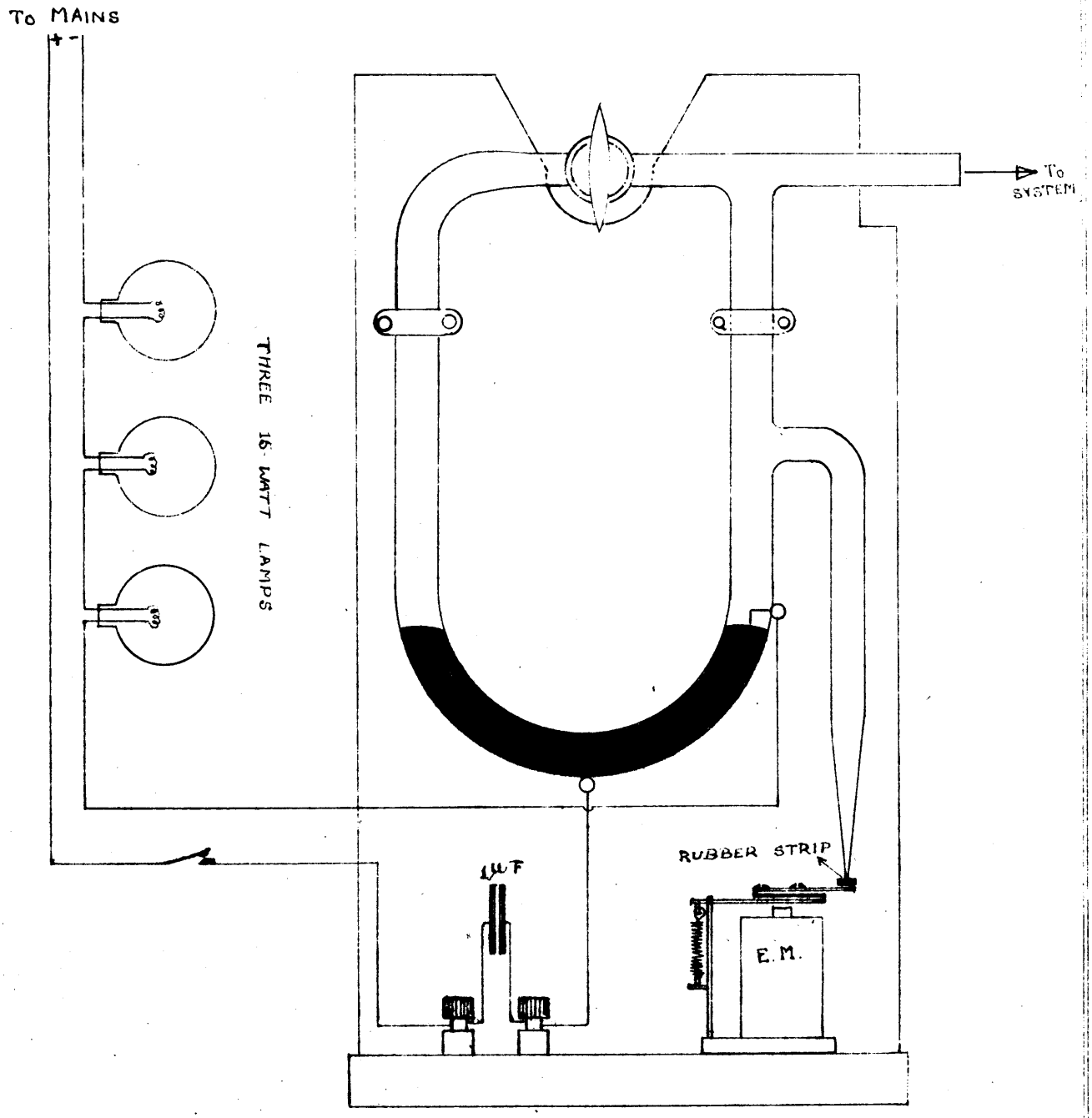
CONDENSATION TYPE LATENT HEAT APPARATUS.



manipulating a hand-operated valve and noting the level of mercury in the manometer. For a more accurate control of pressure inside the system an Automatic Control - an electrical device described by Cryder and Finalborgo[54] - was also used. It is shown diagramatically in Fig. 5.11 (see also Plate V - I). It was made of glass, with Hg in the U-bend and had two Pt leads fused to it. It depends for its performance upon the response of the air in the left limb to the fluctuations of pressure in the system. Normally, the narrow nozzle (about 0.5 mm.i.d.) remained closed by the lever which was operated by an electromagnet. The electromagnet was operated directly from 250 V mains by including 3 - 15 watt lamps in series and a 1 μF condenser in parallel. When the pressure in the system fell, the mercury moved up in the right limb, completed the circuit, and released air into the system till the pressure was restored, when the mercury moved down and broke the circuit. A large aspirator included in the assembly served as a balancing unit.

To obtain the desired pressure in the system, the vacuum pump was started and the stop-cock of the automatic control was opened. The hand-operated valve was carefully manipulated so that the desired pressure was established. The stop-cock of the automatic control was now closed, thus segregating the air in the left limb, after which the pressure was automatically maintained, so that there was no visible movement of

FIG. NO. 5·11 AUTOMATIC PRESSURE CONTROL



the mercury level in the manometer, suggesting a variation of less than ± 0.1 mm. Hg.

EXPERIMENTAL PROCEDURE:-

During the admission of vapour into the calorimeter bulb, the coil around the inlet tube was kept heated by current from the mains through a variable resistance whose magnitude was fixed by a preliminary experiment in which such a minimum current was passed through the coil that on opening the stop-cock, V_2, and closing V_1, no vapour was seen to condense immediately before entering the calorimeter.

The calorimeter contained 1500 c.c. of water. The bulb was first weighed and then the apparatus assembled. The vacuum pump was started and the desired pressure established in the system. The current in the heating coil was now switched on. The liquid was set boiling, valve V_1 opened and V_2 closed and the stirrer started. In the meantime, the regular rise or fall of the tmperature of the calorimeter was observed. Valve V_2 was now opened and V_1 closed and the vapour admitted into the calorimeter for some time. V_1 was now opened and V_2 closed and the maximum temperature of the calorimeter and the final regular rate of fall of the calorimeter temperature noted. The bulb was weighed again.

CALCULATIONS:-

The latent heat was found from the following relationship:-

$$w\left[L + s\,(T_1 - T_2)\right] = E \times \Delta T$$

where

w = Weight of vapour condensed;

L = Latent heat of vaporisation;

s* = Average specific heat of the liquid in the range, T_1 to T_2;

T_1 = Temp. of vapour;

T_2 = Final Temp. of calorimeter; and

ΔT = Corrected rise of temp. of calorimeter;

E = Equivalent of the Calorimeter (with 1500 c.c. water).

The temperature rise was corrected for radiation and similar effects in the usual way.

Water Equivalent of the Calorimeter:-

The calorimeter contained 1500 c.c. of distilled water. The equivalent was found by two methods, (1) Using Steam;

(2) " Hot Water at known temp.

---

*Sp. Heat of Toluene was taken from the nomograph in Ref.3, Page 401.

Good agreemet was obtained between the results obtained by the two methods. These are set out in Table 5.1.

Latent Heat of Toluene:-

Only some of the results obtained with this liquid are given in Table 5.11 to show how the results varied widely even at the same pressure. With toluene it was almost impossible to send just the right amount of current through the heating coil to prevent condensation and yet not to introduce any superheat into the vapour. At low pressures, a second difficulty was encountered, viz., some of the vapour remained uncondensed in the bulb and escaped through the outlet tube into the condenser and receiver attached to the outlet to the bulb. In so doing it partly condensed on the outlet tube and drained back into the bulb. This difficulty could have been avoided by using a metal bulb of good conductivity. One would, however, still be left with the first source of error, and therefore, this apparatus was abandoned.

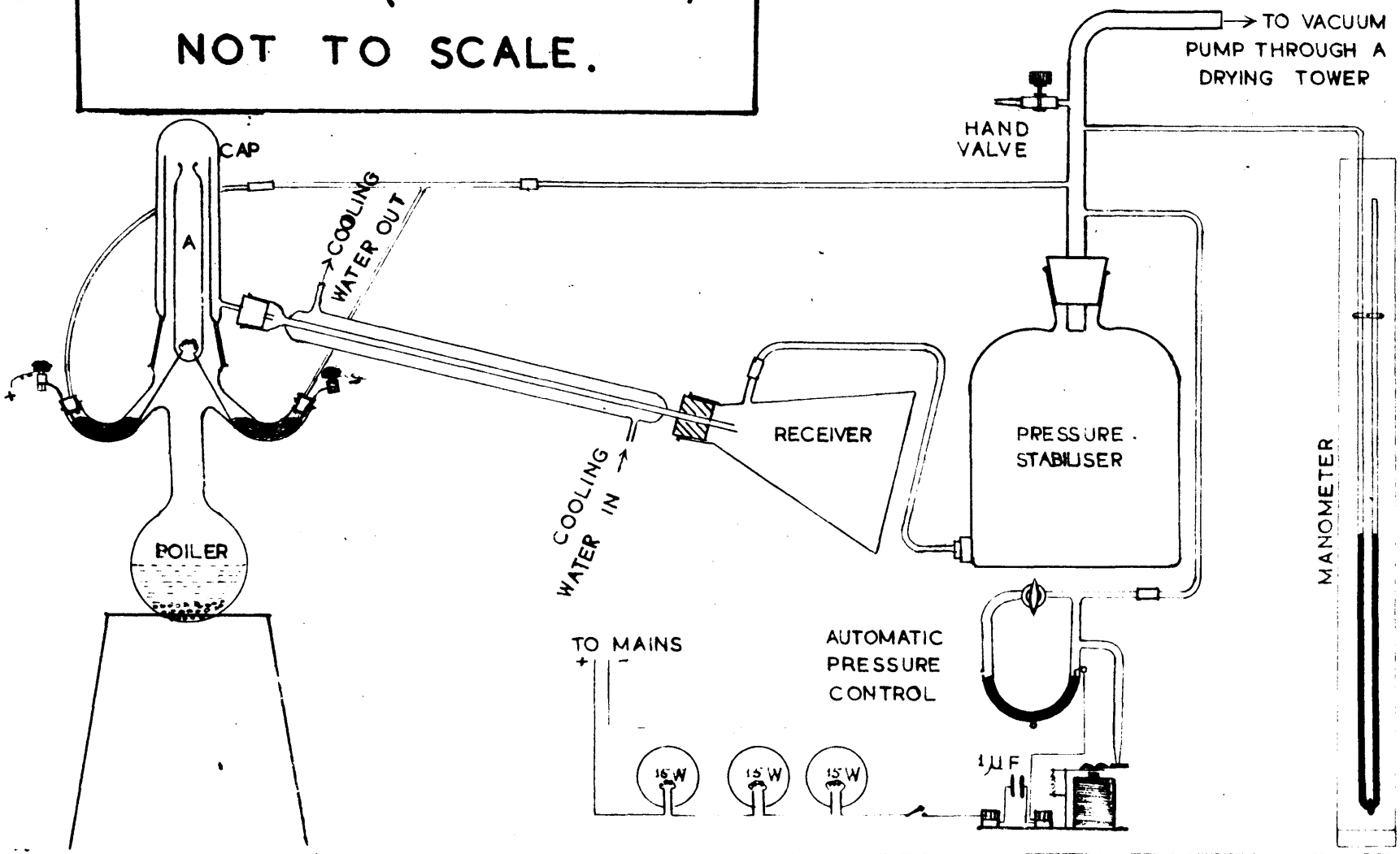
B. ELECTRICAL TYPE APPARATUS.

As the condensation system had failed, the electrical apparatus shown in Fig.5.2 was constructed. It consisted of a Test Tube, A, about $4\frac{1}{2}$ in. long by $\frac{5}{8}$ in. o.d., in which the experimental liquid was boiled by electrical energy while surrounded by its own saturated vapours, so that only the latent heat had to be supplied to cause it to boil. Two leads fused into the tube carried a coil of 0.004 in. dia. Pt wire. The leads dipped into pools of Hg kept in the curved side-tubes of the neck of a 250 c.c. Round-Bottom flask, to which a cap with a ground-glass joint and a side-tube fitted. A thick wrought iron lead, passing through a rubber bung fitted to each of the side-tubes, and dipping into the pools of Hg, allowed electrical connections to be made to a voltmeter, on the one hand, and to a battery an adjustable resistance and an ammeter, on the other. The cap was connected to a condenser and receiver. The pressure in the system could be maintained at the required level by the control devices already described in the previous section. A narrow tube passing through each of the rubber bungs and communicating with the air gap above the pool of Hg in the side-tubes, was also connected to the vacuum line through a Y-tube. A large quantity of glass-beads was placed in the boiling flask to prevent bumping and it

LATENT HEAT APPARATUS. (ELECTRICAL).

NOT TO SCALE.

FIG. 5·2.



was heated directly by a low flame through several thicknesses of asbestos paper. This was found to be more satisfactory than the use of a liquid bath. The heating coil of the Test Tube was coated with finely-divided Pt by repeatedly dipping into a strong solution of $PtCl_4$ and heating electrically to red heat. The leads to the heating coil were 0.02 in. dia. Pt wire.

EXPERIMENTAL PROCEDURE:-

A suitable amount of liquid was taken in "A" and the tube weighed with its contents (W_1). The apparatus was assembled and the desired pressure established. Heating of the flask was then begun and the liquid in the tube heated in the vapour for 20 min. The experiment was now interrupted and the liquid allowed to cool. The test-tube was weighed again (W_2). The difference between these two weights gave the Initial Loss of Weight, ($W_1 - W_2$), on heating the liquid for 20 min. The apparatus was assembled again, vacuum established and the liquid in the flask set boiling till some of it distilled over. The current was now switched on through the heating coil and readings of the voltmeter and the ammeter taken every minute. After some minutes the current was switched off, the time noted, and the test-tube weighed again after cooling (W_3).

($W_2 - W_3$) constituted the final loss of weight. The actual loss of weight caused by the electrical energy was found by correcting the second loss of weight figure from the data of the first period.

RESULTS:-

The following liquids have been used:-

(1) Benzene - Table 5.2; atmospheric pressure only;

(2) Ethyl Alcohol, 95.6% by weight - Table 5.21;

(3) Toluene - Table 5.22.

The pressures in the last two cases range from atmospheric downwards. The determinations on benzene were made in order to test the performance of the apparatus. These results agree closely with the value, 94.34 cals/gm., given by Matthews et al[66].

.....

DETERMINATION OF THE VAPOUR PRESSURE VS. BOILING POINT CURVES FOR ETHYL ALCOHOL AND TOLUENE.

In the above determinations of latent heats it was only possible to note the pressure under which the test was carried out. To be able to correlate latent heat with boiling point, it was necessary to find the vapour pressure-

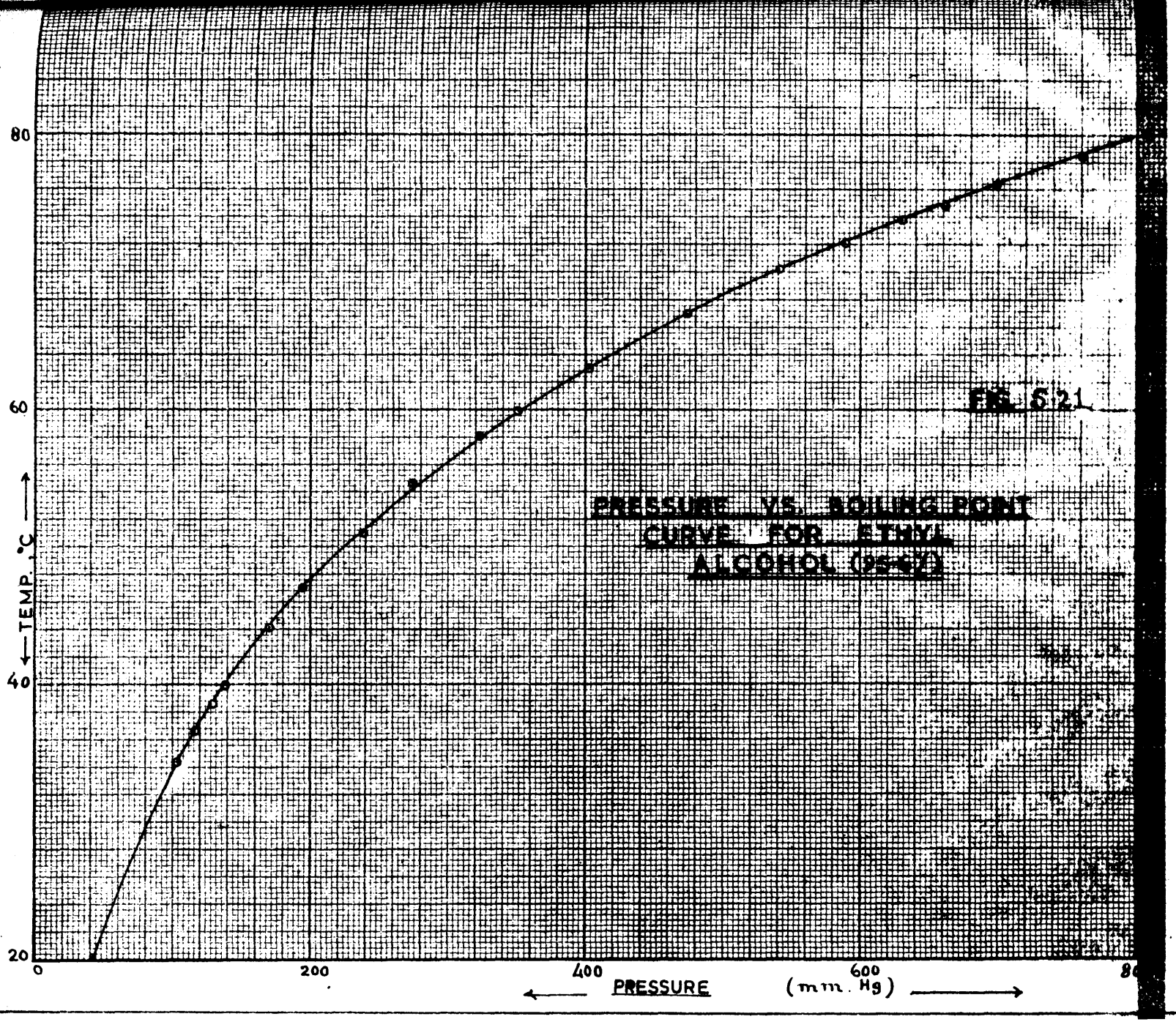


FIG. 5.21

PRESSURE VS. BOILING POINT CURVE FOR ETHYL ALCOHOL (95%)

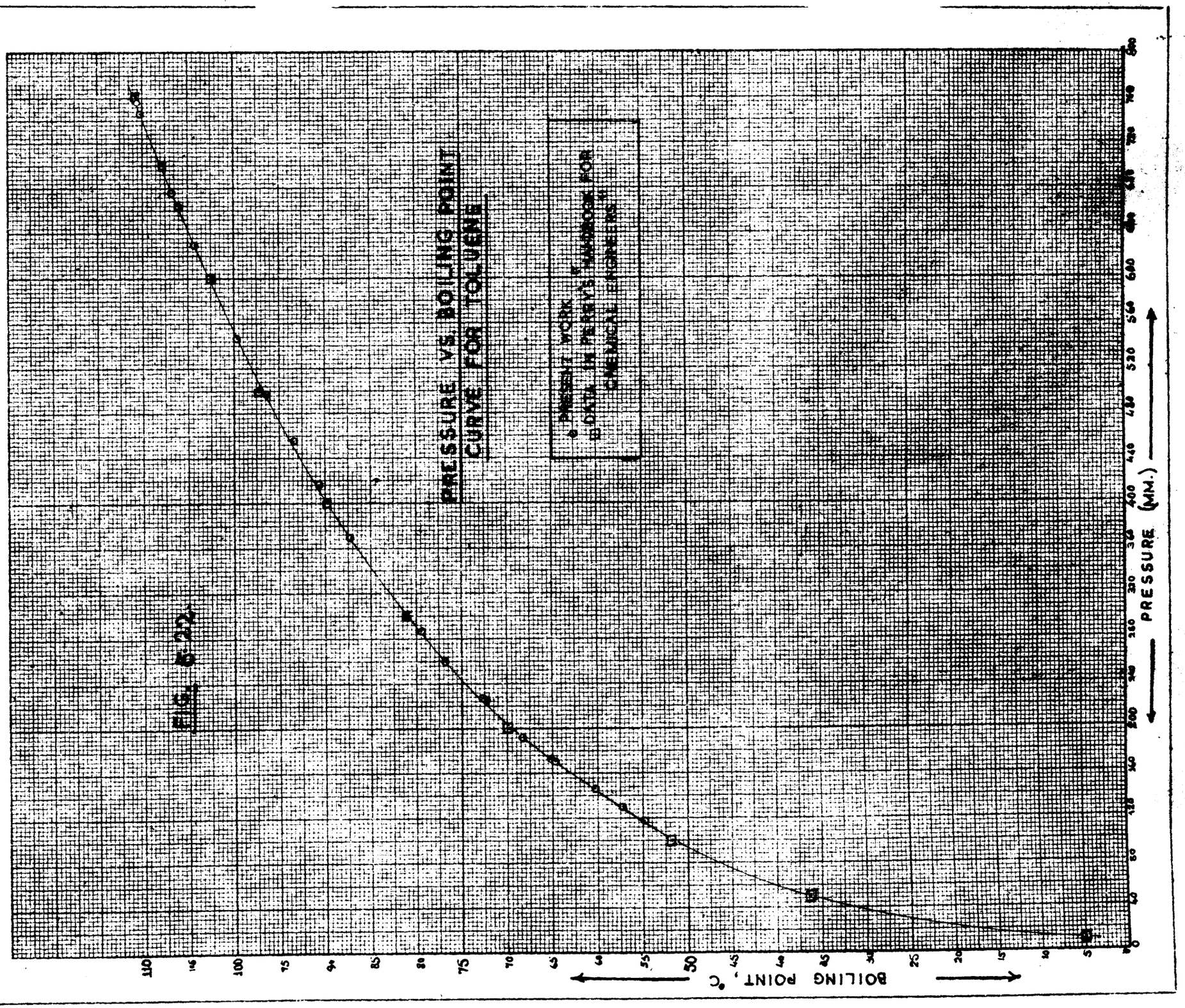

PRESSURE VS BOILING POINT CURVE FOR TOLUENE
PRESENT WORK
DATA IN PERRY'S HANDBOOK FOR CHEMICAL ENGINEERS
BOILING POINT, °C
PRESSURE (MM.)

FIG. 22

temperature curves for the two liquds.

This determination was made by attaching a reflux condenser, through a cork, to a 1-litre boiling flask and connecting the top of the condenser to the pressure maintenance system. A calibrated thermometer passed through the cork fitted to the mouth of the flask. The liquid was made to boil fairly vigorously under various pressures, and the boiling points and the corresponding pressures noted. The resuts are given in Tables 5.3 and 5.31, for ethyl alcohol and toluene, respectively.

A curve was then plotted for boiling point vs. pressure for each liquid (Figs. 5.21 and 5.22, respectively). For toluene, the vapour pressure data given in Ref. 67, Page 383, were also plotted along with the present data and the points are found to lie on the same curve (Fig. 5.22), showing the close agreement between the two. It was found that

B.P. of Et.OH (95.6%) at 760mm. Pressure = 78.5°C.

" " " Toluene " "" " = 110.5°C.

.....

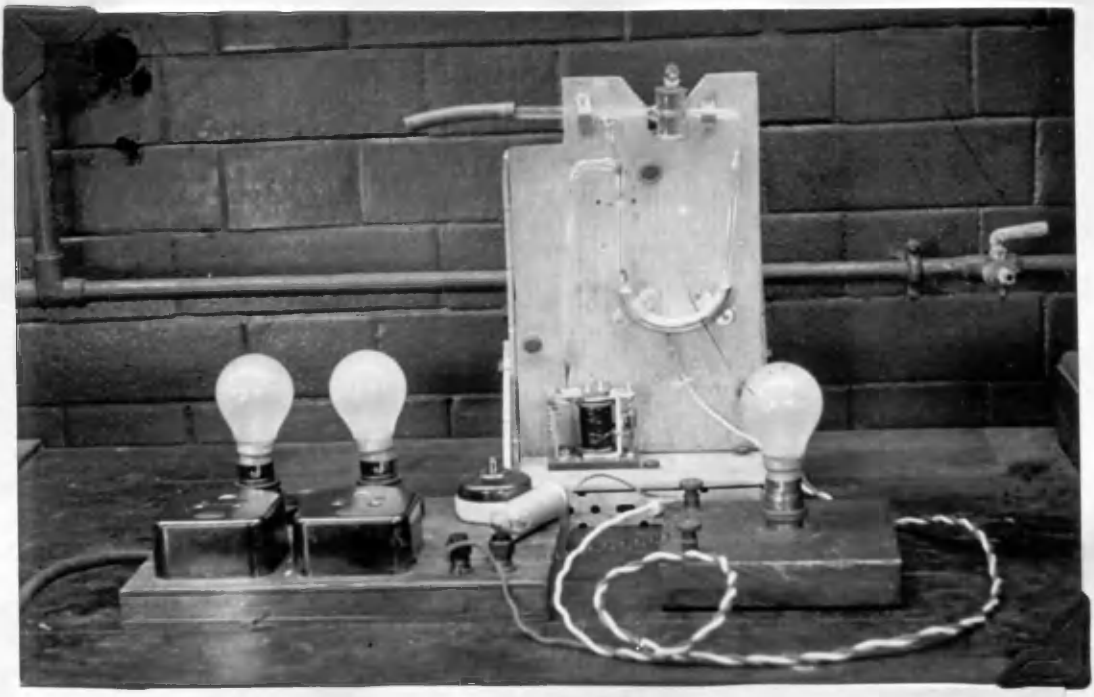


Plate. V-I. Automatic Pressure Control.

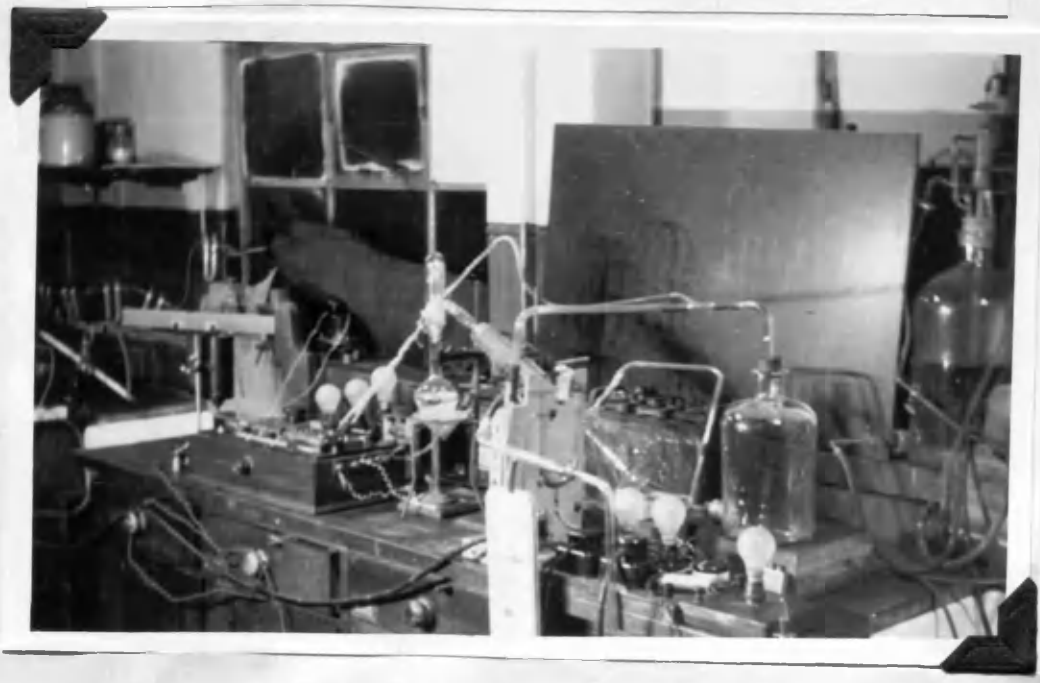


Plate. V-II. Electrical Apparatus for Latent Heat.

CORRELATION OF BOILING POINT AND LATENT HEAT

With the help of these plots of B.P. vs. Pressure the temperatures corresponding to the pressures under which the latent heat determinations were made, could be read out. A plot of Latent Heat vs. Temperature was now made for both the liquids. These plots are shown in Figs. 5.3 and 5.31, respectively.

Since these determinations were made, Hagenmacher[60] published calculated values of the Latent Heat of Toluene at various temperatures, based on the vapour pressure data of Willingham et al[65]. The present results on toluene and those given by Hagenmacher were both plotted together on the same coordinates. Both sets of values are found to lie on the same curve.

From these plots the latent heat of toluene at atmospheric pressure is found to be

= 86.1 cals/gm.,

and that of 95.6% ethyl alcohol

= 223.5 cals/gm.

The value given by Brown [62] for pure ethyl alcohol is 216.4 cals. per gm.

ACCURACY OF RESULTS:-

The measurement of current strength could be secured to within ± 0.2% and that of weight was so

FIG. 5·3.

BOILING POINT VS LATENT HEAT CURVE FOR ETHYL ALCOHOL, 95%

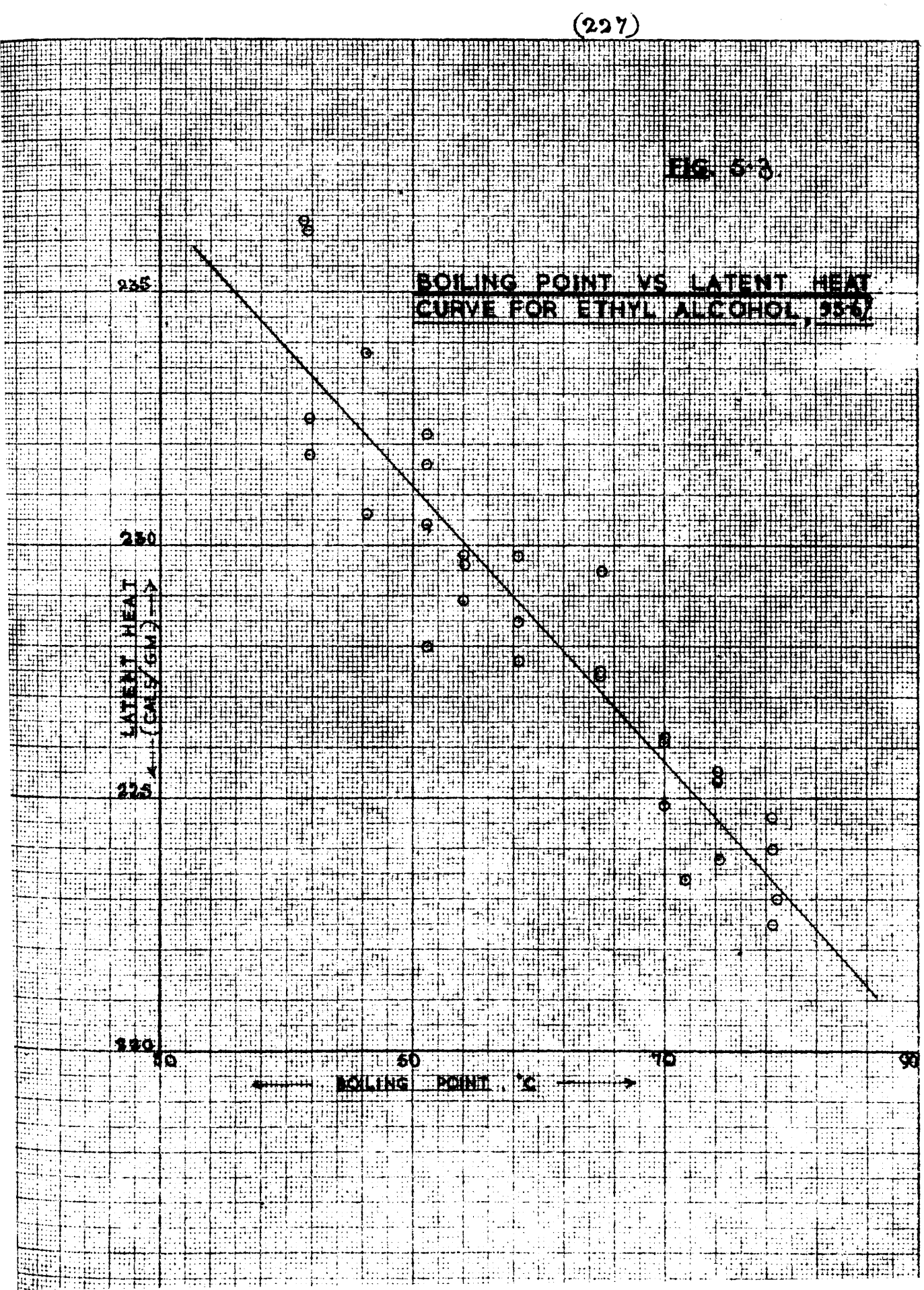
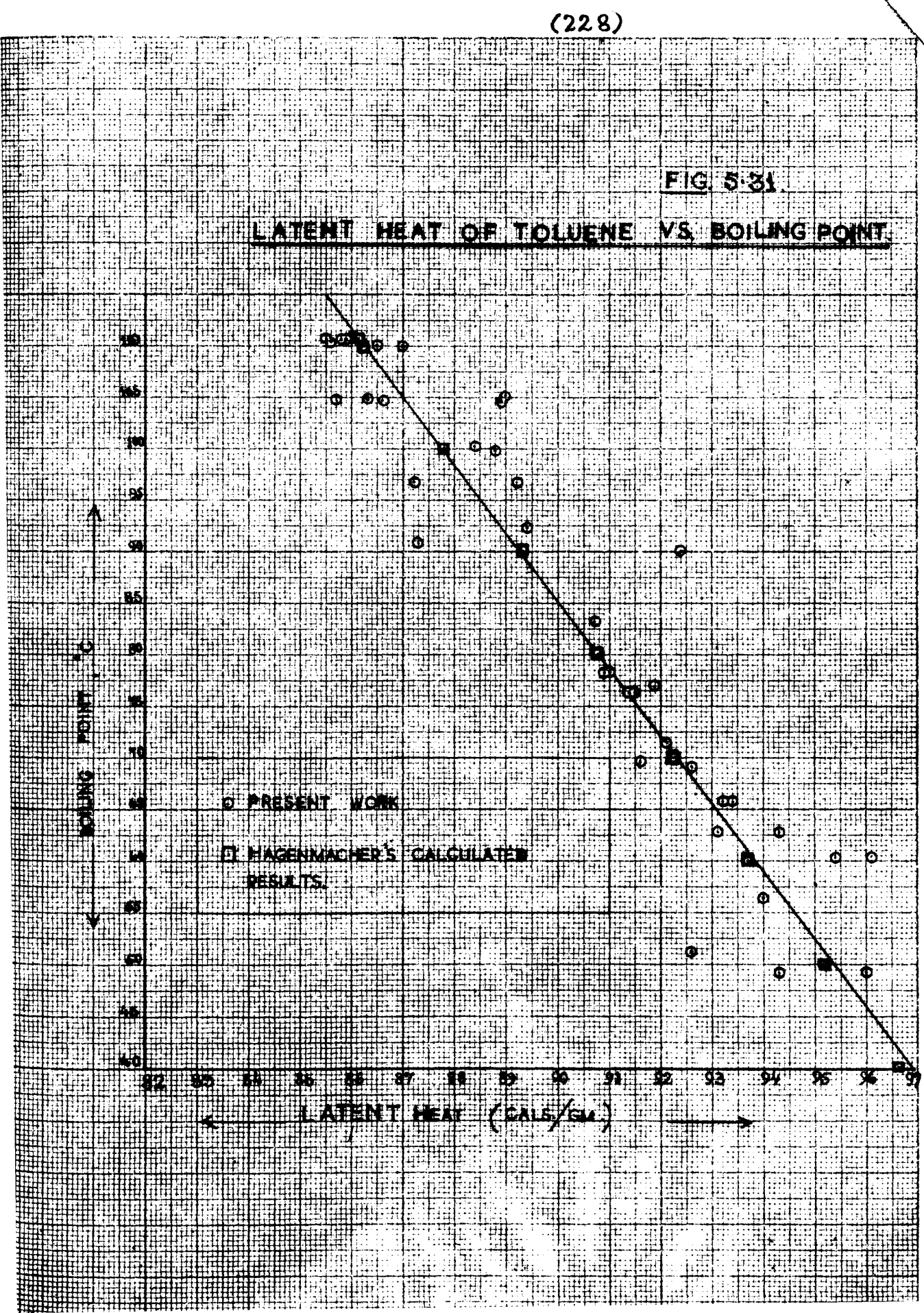


FIG. 5·31.

LATENT HEAT OF TOLUENE VS. BOILING POINT.



accurate as to make any errors negligible. However, the voltage measurement was not so accurate and errors might have amounted to ± 1%. The individual results may, therefore, vary by as much as ± 1.2%, but the probable error should not be more than ± 0.5%.

.....

OBSERVATIONS ON BOILING.

During these investigations some interesting observations were made on boiling. To obtain a smooth boiling in the boiling flask, porous porcelain pieces, glass-wool, and glass beads were tried. It was found that a thick bed of glass beads gave as good a result as any of the other two or even better. When the beads were freshly added they initiated boiling without much difficulty even at low pressures; but, if the liquid was boiled for some time under vacuum, allowed to cool and then reheated under vacuum, there was a tendency to bump. Great care was necessary, therefore, in initiating boiling under vacuum. The liquid had to be heated very slowly and cautiously and when it was felt that it had reached its boiling point, a little stronger heat was applied to a point near the edge of the glass-bead bed when bubble formation usually occured, and once begun, continued more or less smoothly. If, by chance, some mercury fell over the bed

of glass beads, it caused serious bumping.

The boiling of the liquid over the heating coil in the test-tube presented a difficult problem. When fresh Pt wire was used it gave smooth boiling for some time but quickly became inactive within a few tests. There was, now a great tendency for the liquid to superheat and bump. Various aids like small glass beads, small pieces of porous porcelain, powdered porcelain and glass-wool were all tried without avail, if the Pt wire had itself become inactive.

This led to the conclusion that it was the condition of the heated wire itself that mattered. Consequently, its surface was first coated with carbon by making it glow in the vapour of toluene when the latter underwent thermal decomposition and deposited carbon on the wire. This carbon-coated wire was fairly effective at atmospheric pressures, but its activity quickly fell during tests under vacuum.

Ultimately, a coating of finely-divided Pt on the wire was tried. This was obtained by soaking the coil in a concentrated solution of $PtCl_4$ and passing sufficient current to make it glow. This Pt-covered wire proved most effective. It was necessary, however, to renew the coating at intervals.

When the wire - whether coated or uncoated - had become inactive, it was found that even when the boiling had commenced in an explosive manner after excessive superheating,

it would not continue. The liquid used to bump after relatively long quiet intervals.

.....

COMMENTS ON THE APPARATUS.

(1) Brown used his apparatus only at atmospheric pressure. On the basis of the present work it could be safely claimed that the apparatus in its present form could be used at low pressures.

(2) To avoid bumping the flask must contain a thick bed of glass-beads and the coil must be coated with finely-divided Pt.

(3) The pressure in the system must be maintained steady.

(4½) The success of an experiment depends upon the immediate start of boiling on switching on the current through the heating coil, smooth boiling as long as the current is passing, and its complete stoppage as soon as the current is switched off.

.....

TABLE 5.1.

WATER EQUIVALENT OF CALORIMETER (E).
(Calorimeter contains 1500 cc. Water.

(1) USING STEAM:-

TEST NO.	STEAM CONDENSED (Gms.)	FINAL TEMP. °C.	CORRECTED TEMP.RISE °C.	HEAT EXCHANGED (Cals)	E. (Gms)
1.	8.386	19.32	3.110	5194	1670
2.	8.295	17.77	3.085	5152	1670
3.*	8.869	20.88	3.328	5481	1643
4.	8.072	20.94	2.995	4981	1664

(2) USING HOT WATER:-

TEST NO.	HOT WATER ADDED (Gms)	TEMP.OF H.WATER °C.	FINAL TEMP. °C.	CORRECTED TEMP.RISE °C.	HEAT EX CHANGED (Gals)	E. (Gms)
5.	70.80	33.093	14.10	0.806	1345	1669
6.	75.37	36.290	17.03	0.872	1451	1665
7.	62.34	37.980	16.08	0.820	1365	1666

Average..... 1667

* Rejected, being too inconsistent.

TABLE 5.11.

LATENT HEAT OF TOLUENE .

(Condensation Type Apparatus.)

TEST NO.	PRESSURE (mm.)	WEIGHT OF TOLUENE CONDENSED (Gms)	TEMP. OF VAPOUR °C.	FINAL TEMP. OF CALORIMETER °C.	CORRECTED RISE OF TEMP. °C.	HEAT EXCHANGED cals.	L. cals/Gm.
1.	760	32.392	110·5	16.50	2.080	3468	65.0
2.	,,	20.728	,,	16·51	1.270	2117	60.2
3.	,,	19.870	,,	17.30	1.173	1956	56.7
4.	,,	13.188	,,	20.20	1.005	1676	86.5
5.	,,	14.118	,,	21.20	1.038	1729	82.5
6.	,,	19.714	,,	15.00	1.569	2615	90.0
7.	,,	15.822	,,	16.03	1.106	1841	74.3
8.	263	18.357	75.0	17.25	1.156	1928	78.8
9.	260	21.310	74.5	18.60	1.197	1960	68.7

TABLE 5.2

LATENT HEAT OF VAPORISATION OF BENZENE

(Electrical Apparatus)

TEST NO.	PRESSURE	WEIGHT LOSS (gms)	VOLTS	AMPERES	TIME (secs)	LATENT HEAT (cals/gm)
1.	Atmos.	2.632	4.00	0.865	300	94.40
2.	,,	4.180	4.00	0.859	480	94.15
3.	,,	1.864	2.82	0.870	300	94.40
4.	,,	1.901	2.84	0.880	300	94.30

TABLE 5.21

LATENT HEAT OF ALCOHOL (95.6%)

(Electrical Apparatus)

TEST NO.	PRESSURE (mm)	WEIGHT LOST (gms)	E (Volts)	I (Amps)	TIME (min)	LATENT HEAT (cals/gm)
1.	148	3.243	7.75	0.985	7	236.4
2.	151.5	3.341	8.10	0.970	7	236.2
3.	,,	3.313	7.95	0.962	7	231.8
4.	,,	2.538	8.39	0.981	5	232.5
5.	186	3.544	8.31	0.987	7	233.8
6.	,,	2.985	8.12	0.985	6	23066
7.	234	2.484	8.20	0.980	5	232.1
8.	235	2.464	7.95	0.985	5	228.0
9.	,,	2.890	7.96	0.976	6	230.4
10.	,,	2.805	7.78	0.972	6	232.2
11.	282	3.062	8.40	0.973	6	229.8
12.	,,	3.003	8.29	0.966	6	229.6
13.	,,	2.785	7.76	0.962	6	228.9
14.	325	3.029	8.10	0.990	6	227.7
15.	,,	2.956	8.00	0.987	6	229.8
16.	,,	2.891	7.95	0.966	6	228.5
17.	435	3.009	8.15	0.985	6	229.5
18.	,,	2.987	8.10	0.975	6	227.4
19.	,,	3.039	8.16	0.985	6	227.5
20.	539	3.556	8.24	0.973	7	226.2
21.	,,	4.038	8.16	0.970	8	224.9
22.	,,	3.564	8.26	0.973	7	226.1
23.	577.5	3.677	8.39	0.975	7	223.4
24.	640	3.604	8.33	0.971	7	225.3
25.	,,	4.118	8.30	0.968	8	223.8
26.	,,	4.035	8.22	0.965	8	225.5
27.	760	4.428	8.63	0.995	8	222.5
28.	,,	4.340	8.60	0.985	8	224.0
29.	,,	4.267	8.50	0.983	8	224.6
30.	770	4.063	5.33	1.975	6	223.0

TABLE 5.22

LATENT HEAT OF TOLUENE

(Electrical Apparatus)

TEST NO.	PRESSURE (mm)	WEIGHT LOST	E (volts)	I (amps)	TIME (secs)	LATENT HEAT (cals/gm)
1.	128	2.012	2.15	0.765	480	94.0
2.	,,	1.913	2.15	0.757	480	97.5
3.	146.	1.680	2.14	0.746	420	95.4
4.	,,	1.932	2.15	0.752	480	96.1
5.	160	2.601	2.65	0.922	420	94.3
6.	161	2.963	2.80	0.981	420	93.1
7.	176	1.774	2.10	0.726	300	93.2
8.	177	2.164	2.85	0.994	300	93.4
9.	198.5	3.100	2.88	0.992	420	92.6
10.	201	3.15	2.90	0.990	420	91.6
11.	215	0.934	2.06	0.727	240	92.1
12.	254.5	4.503	2.91	0.987	600	91.5
13.	,,	2.994	2.98	0.997	360	85.5
14.	257.5	3.274	2.98	1.000	420	91.4
15.	262	2.360	3.00	1.008	300	91.9
16.	270	3.304	3.00	1.005	420	91.0
17.	271	3.266	2.97	0.996	420	90.9
18.	323	3.213	2.96	0.981	420	90.7

TABLE 5.22, (continued)

TEST NO.	PRESSURE (mm)	WEIGHT LOST (gms)	E (volts)	I (amps)	TIME (secs)	LATENT HEAT (cals/gm)
19.	414	3.407	3.00	0.988	420	87.3
20.	433.5	3.509	3.00	0.987	420	84.8
21.	434.5	3.330	3.01	0.985	420	89.4
22.	439	3.553	3.04	0.990	420	85.0
23.	555	3.427	3.07	0.988	420	88.8
24.	558	3.205	3.00	0.991	420	93.0
25.	,,	3.513	3.10	0.998	420	88.4
26.	637	3.636	3.18	0.986	420	86.6
27.	,,	2.767	3.20	1.001	300	83.2
28.	,,	2.556	3.25	1.007	280	85.7
29.	,,	3.708	3.30	0.995	420	88.9
30.	644	3.693	3.20	0.992	420	86.3
31.	648	3.654	3.27	0.990	420	89.0
32.	743	3.771	3.30	0.991	420	87.0
33.	761	3.785	3.28	0.987	420	85.8
34.	765	3.809	3.27	0.992	420	85.5
35.	766	3.800	3.29	0.993	420	86.1
36.	90	1.293	2.38	0.893	240	94.3
37.	,,	1.242	2.35	0.885	240	96.0
38.	96	1.311	2.37	0.892	240	92.6
39.	402	1.903	4.72	0.865	180	92.4
40.	496	4.037	4.20	0.854	420	89.2
41.	,,	4.141	4.20	0.855	420	87.2
42.	760	2.290	2.92	0.938	300	85.8
43.	,,	2.270	2.91	0.932	300	85.6
44.	,,	2.222	2.90	0.923	300	86.5

TABLE 5.3

BOILING PT. OF ETHYL ALCOHOL* UNDER VARIOUS PRESSURES

PRESSURE (mm).	BOILING POINT (°C).
104	34.4
116	36.5
127	38.7
137	40.0
170.5	44.1
193.5	47.1
237.5	51.2
275	54.6
322	58.1
351	60.0
402	63.1
474	67.0
540	70.1
588	72.1
629.5	73.8
652.5	74.8
698	76.3
760	78.5

*95.6% by weight.

T A B L E . 5.31.

BOILING POINT OF TOLUENE UNDER VARIOUS PRESSURES.

PRESSURE(mm.)	BOILING POINT (°C)
117.5	54.9
129.0	57.2
146.5	60.4
170.5	64.7
172.5	65.1
192.0	68.2
225.0	72.4
227.0	72.7
259.5	76.6
287.0	79.5
369.0	87.1
416.0	90.6
455.0	93.5
497.0	96.3
547.0	99.6
630.0	104.3
663.0	106.0
676.0	106.9
746.0	110.1
756.0	110.5

C O N C L U S I O N.

D I S C U S S I O N

1. BOILING.

During latent heat determinations with the electrical apparatus, it was observed that boiling does depend upon the presence of agents which aid bubble formation either by supplying bubble nuclei in the form of adsorbed gases or vapours in their surfaces, or, by modifying conditions adjacent to the heating surface. It was found that, when the heating platinum coil had itself become inactive in initiating bubbles, the addition of ebullators like porous porcelain, glass-wool and glass-beads was only of short-lived assistance in inducing bubble formation, especially at low pressures. This would lead one to the conclusion that the adsorbed gases and vapours in their surfaces proved helpful at the outset, but as these were dislodged by boiling under vacuum, the ebullators became inactive. The behaviour of ebullators in the flask was a similar one. There was, however, one important difference, viz., the presence of a thick bed of glass-beads in the flask gave smooth boiling, once bubble formation had been induced, whereas, in the case of the liquid heated by platinum coil in the test tube, there was flashing at intervals.

For smooth boiling, the coil had to be coated with finely-divided platinum. This would suggest that a different mechanism was operative in the two cases. However, it appears probable that in each case the process of smooth boiling depends upon the presence of cavities which restrict the free convection of the liquid. In this condition the liquid has a better chance of local superheating. Any adsorbed gas or vapour in this cavity would easily initiate a bubble without excessive superheating. When a bubble is escaping from this cavity, some"trace" of vapour might be left behind by the bubble in contact with the heating surface, and this would serve as the nucleus for a new bubble. Looked from this angle the apparent difference between the two cases disappears. In the case of the boiling flask, the cavities were provided by the unfilled spaces between the surface of the flask and that of the glass beads. In the case of the coated wire the cavities might have been created by the uneven deposit of the finely-divided platinum. This rough platinum surface gave smooth boiling for an indefinite period even under vacuum, whereas a deposit of carbon on the platinum surface was less efficient in promoting boiling and lost its activity quickly. Normally one would expect that the deposit of carbon would be porous in nature and should give easy boiling like the finely-divided platinum. Since this was not found to be the case, the dis-

crepancy must be explained by assuming that the carbon deposit changed in character. It is well known that active charcoal loses its activity for adsorbing gases in course of time and has to be reactivated by special treatment. It is possible that this carbon deposit became fouled in a similar manner. No attempt was made to revive it and test its activity again.

From the above discussion it is evident that a foreigh gas in the liquid, whether in solution in it or adsorbed on solid surfaces present in it, gives bubbles much more easily that the liquid vapour itself. The origin of a bubble of vapour in a saturated or superheated liquid, and that of a bubble of a foreign gas inside the liquid, are subject to the same laws of pressure relationships. Because of its natural attraction for its own vapour, the liquid would be reluctant to release a bubble of its vapour, whereas, if it is assumed that the pressure of the foreign gas increases enormously as the temperature of the liquid is raised, the relatively easy formation of a bubble of the foreign gas inside the liquid could be explained.

The rough surface might also be helping in the development of the nucleus bubble by providing conical "DIPS" or conical"TIPS" as postulated by Cassel[34]. On the basis of his thermodynamic theory of bubble formation, Larson[10] concluded that surface roughness or curvatures of molecular or

unit crystal magnitude helps in the formation of initial bubbles. From Cassel's theory also it could be deduced that the critical size of the nucleus bubble of small diameter could be obtained without excessive superheating only if the contact angle were large and the conical dip or conical tip were minute in size, comparable with that of the nucleus bubble. Both these theories lead to the conclusion that for bubble formation without excessive superheating, the elements of surface roughness must be small in magnitude. The formation of finely-divided platinum form $PtCl_4$ would produce atomic Pt, and depending upon the temperature of decomposition, a smaller or larger number of atoms would agglomerate to give crystals. Since the temperature used in the decomposition of $PtCl_4$ was not very high, the crystalline masses obtained would be minute in size and the deposit porous in nature. In the decomposition of toluene vapour, however, complex reactions giving large molecules are possible, and even when complete dehydrogenation of the molecules has been achieved, the residual masses produced would be rather large agglomerates. If therefore, minute size of elements of surface roughness be regarded as the chief factor aiding ebullition, the difference between the initial behaviour of finely-divided Pt and C could be explained, and the present observations would lend support to the views of Cassel and of Larson, and also to the observations

of Sauer et al[1] who found that a thin film on copper gave a better heat flux.

When liquids were boiled over electrically heated wires, the bubbles at the moment of their detachment from the surface, were comparable in size with the diameter of the wire being used. The bubbles formed in the boiling flask were much larger than those formed in the test-tube over the coated platinum wire. In a simple boiling of water in a beaker, too, it is usually seen that large steam bubbles leave the surface. This would suggest that the size of the initial bubble largely depends upon the curvature of the surface on which the bubble originates. A smooth surface with a small curvature gives large bubbles. A rough surface gives smaller bubbles as was also noted by Jakob[9]. From the point of view of heat transfer, therefore, a rough surface is preferable, since the formation of smaller bubbles leaves a larger portion of the heat transfer surface to be wetted by the liquid which quickly regains its superheat.

2. Boiling in a Vertical Tube, Natural-Circulation, Evaporator and the Division of the Tube into Boiling and Non-Boiling Sections.

With the glass-tube evaporator the appearance of the liquid inside the tube could be easily observed.

The fluid column was actually found to consist of boiling and non-boiling sections. These observations have already been recorded in detail in Chapter I., and generally fall in line with those of Brooks and Badger[44] and of others cited by these authors. Only in one respect there was some difference, viz., the distribution of phases in situation (2) - (see Introduction, Part III) - was in no way uniform. This was possibly due to the larger diameter of tube used in the present work than the one used by Brooks and Badger. "Slug" action is clearly the result of bubble coalescence and this coalescence becomes all the more marked in situation (3) where the vapour forms one single column with the liquid on the sides of the tube. Due to the large diameter of the tube the bubbles pushed their way up in a zig zag manner through the liquid, making the phase distribution un-uniform.

The zone of separation between the boiling and the non-boiling sections was generally indistinct and this situation was accentuated by the bubbles of dissolved air in the feed, which aided premature bubble formation. When the feed was deaerated and the temperature drop was low, this boundary between the two sections became clearer. Despite deaeration some air remained dissolved in water and initiated smooth boiling, whereas ethyl alcohol and toluene could be so thoroughly deaerated that they showed consider-

able tendency to undergo excessive superheating.

Temperature explorations along the axis of the tube showed that the maximum temperature of the liquid roughly coincided with the zone of separation of the boiling and the non-boiling sections, so that one could say within an error of about ±1.5 inches where the maximum temperature would occur. Thus, boiling, as it is normally understood, does not commence till the liquid reaches or at least closely approaches its maximum temperature inside the tube. Air bubbles would normally aid premature vaporisation by virtue of the partial pressure of the air inside the bubble. The diffuse boundary between the boiling and the non-boiling sections is explained in this way. For the evaluation of the boiling coefficients, therefore, the tube was divided into boiling and non-boiling sections in the manner done by Brooks and Badger[44].

Even with the metal tube evaporators, the temperature drop from the tube surface to the feed liquid was not high. There seems little justification to suppose, therefore, that incipient boiling could have occurred in the non-boiling section on the walls of the tube, apart from occasional release of air bubbles.

An examination of the tables in Chapters I and II would show that coefficients, both overall and film, are consistently higher for the boiling section than for

the non-boiling section. Coefficients based on the entire length of the tube are intermediate between the two and are remarkably constant for any liquid-tube pair. With all three vertical, natural-circulation, evaporators the following generalisations could be made :-

(1) Only a small variation was noted in the value of the heat load, q, although the feed rate varied by several hundred percent for each liquid-tube pair.

(2) Roughly constant value of the overall coefficient, U, based on the integrated overall temperature drop, Δt_m , for the entire tube, were obtained.
It appears that for a given pressure in the system, and a given temperature of heating water in the jacket, the boiling and non-boiling sections so adjust themselves for varying feed rates as to give roughly constant values of q and U, much as the bodies of a multiple effect evaporator automatically adjust their temperature drops. The fixing of the pressure has determined the overall temperature difference, and it is clear from the above generalisation that this has been the predominant agent in heat transfer, whether boiling takes place or not. This fact gives the division of the fluid stream into boiling and non-boiling sections a certain degree of unreality. The overall heat transfer is determined by other factors. For this reason, in reporting the present data, the overall coefficients,

U, have also been included.

3. Heat Transfer Coefficients in the Boiling Section.

As a result of determinations on water and ethyl alcohol with the glass-tube evaporator, the overall coefficient for the boiling section, U_B , has been found to increase steadily with temperature drop. There is some reaction to feed rate in that with increasing feed rate the coefficients for water in the copper tube evaporator, for example, first decrease and then increase. For the other two liquids in the same tube there is only a slight tendency to decrease and then the coefficients increase steadily. This behaviour is explained by suggesting that at low feed rates the effect of the amount of vapour predominates, and since this amount is large, the coefficients are also high. On increasing the feed rate, the amount of vapour decreases with consequent decrease in the coefficients. At high feed rates, the fall in the amount of vapour is made up by the increased amount of liquid, resulting in the high values of the coefficients again. It was noted with the glass-tube evaporator that at high feed rates there was increased agitation of the fluid in the boiling section. This would suggest a kind of analogy with the turbulent motion of a fluid that results in

better heat transfer. The boiling film coefficients for water in the copper tube evaporator mostly lie between 2000 and 3000 (B.Th.U./hr/sq.ft/^{o}F.), and compare favourably with the results of Brooks and Badger[44] for similar values of temperature drop and boiling temperature.

The coefficients in the boiling section for toluene have been found to be generally higher than those for ethyl alcohol. For example, with the copper tube, the value of the film coefficient, h_B, for toluene mostly lies between 450 and 630, whereas for ethyl alcohol it mostly lies between 300 and 450. With the forced-circulation evaporator, however, the situation has been reversed; the film coefficients for toluene (mostly 200 to 500) are lower than those for ethyl alcohol (mostly 300 to 600), for similar values of liquid velocity, the temperature drop being roughly constant and of similar magnitude in both the cases. The higher values of the coefficients for toluene in the natural-circulation evaporators may partly be due to the fact that the molar fraction evaporated for toluene in the copper tube, for example, is higher (0.263 to 0.344) than for ethyl alcohol (0.152 to 0.252), for similar values of temperature drop. This difference must be giving much higher fluid velocities for toluene in the boiling section, resulting in better heat transfer.

On the basis of results on the forced-circula-

tion evaporator, the boiling film coefficients, h_B , correspond to fluid velocities of the order of 5 - 15 ft/sec. ; for toluene the values of the film coefficient, h, in the forced-circulation evaporator become comparable with those of h_B only when the liquid velocity has reached a value of 8 ft./sec. This would show the marked superiority of the natural-circulation evaporator.

4. Effect of Surface Tension.

The remarkable effect of reduced surface tension on the nature of boiling in a vertical tube has already been described (Ch.I). With reduced surface tension the formation of bubbles becomes much easier and the bubbles are also stabler. The bubbles mostly develop on the top of the liquid column, and, therefore, do not carry any considerable liquid with them. The reduced surface tension seems to have increased the boiling overall coefficient although its effect was greatly masked by the high resistance of the glass-tube.

5. Temperature measurements in the Vertical Tube.

These should be fairly accurate for the boiling section and for the forced-circulation runs, in both of which there was considerable mixing of the liquid. In the non-boiling section it was observed with the glass-tube

that a fair degree of mixing of the liquid occurred as evidenced by visible convection currents. The regularity of the curves for Temperature Drop vs. Distance from the tube bottom, for the non-boiling section, the appearance of the convection currents, the disturbance caused by the air-bubbles, and the commencement of roughly simultaneous boiling along the whole cross-section of the tube, all lend support to the view that the temperatures recorded by the travelling thermocouple at the axis of the tube could not be far from the average temperature of the bulk of the liquid.

6. Boiling on a Wire and the Boiling Curve.

When a liquid at its boiling point is circulated over a heated wire, boiling does not begin unless a certain minimum flux value has been reached. The magnitude of this minimum (corresponding to which, therefore, there was a minimum temperature drop requirement) was generally higher than those observed by McAdams et al[6] , making allowance for the difference in the wire diameters; it was found to increase with decreasing wire diameter, as also observed by these authors. It increased with increasing liquid velocity. It is possible that the friction head arising from the velocity of circulation, was responsible for the consistently higher values observed here. Ethyl alcohol was

found to show an abnormal tendency for superheating; boiling would not begin until fairly high values of temperature drops of the order of 30°to 35°F were reached, although it would continue down to much lower values of temperature drop.once it had been initiated. That this initial abnormal superheating increased with decreasing wire diameter is somewhat surprising inview of the general belief that on a surface of larger curvature bubble formation is easier. In this respect this result would agree with the observations of Dean[32] who found that sharp edges and points were by no means better promoters of boiling. The minimum values of temperature drops for which visible boiling was obtained, ranged from 10°to 25°F depending upon wire diameter, liquid valocity, and the nature of the liquid.

For water, in the upper part of the nucleate boiling curve, the values of flux for the two wires are of the same order as those obtained by McAdams et al. In the lower part, corresponding to temperature drops of about 10-25°F, the values of flux are somewhat higher, showing that the velocity of liquid aided heat transfer by increasing the turbulence of the liquid. Similarly, in the range of low temperature drops upto about 10°F, the values of flux are higher than would correspond to natural convection heating of water, showing again the effect of velocity in increasing heat flux in this region. For the same

wire the effect of varying velocity has either been negligible or only very slight. A decrease in wire diameter has increased the value of flux upto a temperature drop of about 25° F.

For ethyl alcohol, the form of the curve in the upper nucleate region and also in the film boiling region is the same as generally accepted. For temperature drops upto about 25°F, the effect of velocity and wire diameter has been the same as in the case of water.

Above a temperature drop of about 25°F, for both water and ethyl alcohol, it is found that the curves corresponding to different wires and liquid velocities have a tendency to merge into one another, this tendency being better marked in the case of ethyl alcohol. This result agrees closely with that obtained by McAdams et al. This would suggest, therefore, that the turbulence caused by increased rate of boiling for temperature drops above about 25°F overrides all other factors like velocity of circilation and wire diameter, and the flux rises sharply with temperature drop in the nucleate boiling region. The values of flux are higher for water than those for ethyl alcohol under the same conditions. The effect of contamination has been to reduce flux for the same temperature drop and liquid velocity for water.

SUMMARY.

The following statements are made on the basis of the present investigations :-

(1) Boiling depends upon the presence of ebullators which aid smooth bubble formation by creating cavities on the hot surface and thus modifying convection to give local superheating in the immediate neighbourhood of the heating surface. For a thin platinum wire used for boiling liquids, these cavities are best provided by a thin coating of finely-divided platinum. The nucleus bubbles can originate without much superheating if adsorbed gas or vapour is available either in the surface of the ebullator or in the heating surface itself. In the long run the adsorbed gas or vapour in the surface will be removed. In the absence of adsorbed gas or rough surfaces, bubbles can originate only by the excessive superheating necessary for the fulfilment of the thermodynamic requirements of the process.

(2) Using a glass-tube evaporator, the appearance of the boiling liquid has been found to confirm generally the results of previous investigators. The remarkable effect of surface tension in altering this appearance has been described. The boiling region of water with reduced surface

tension (0.1% solution of Perminal W.A. in water; surface tension about 50% that of pure water) consists entirely of bubbles with only a thin film of liquid on the tube surface. The fluid column consists of boiling and non-boiling regions, and the zone of separation of the two sections corresponds to the maximum temperature of the liquid. The effect of dissolved air is to obscure the boundary between the boiling and non-boiling sections.

(3) Reduced surface tension, obtained by dissolving 0.1% Perminal W.A. in water, has slightly increased boiling coefficients for water, although its effect has been greatly masked by the high resistance of the glass-wall.

(4) The division of a vertical tube evaporator into boiling and non-boiling sections has been confirmed. However, for equipment of the kind used here and for the experimental conditions, employed, it seems more reasonable to treat the tube as a whole, since values of 'q' and 'U' either show a small change with feed rate, or are roughly constant.

(5) Using a glass-tube under natural circulation, and a vertical copper tube under both natural and forced circulation, coefficients have been reported for water, 95.6% ethyl alcohol, and toluene. Overall boiling coefficients have been reported for 0.1% Perminal W.A. aqueous solution

in the glass-tube evaporator. Boiling film coefficients have been reported for water in a vertical, natural-circulation, stainless steel evaporator tube. The film boiling coefficients are the highest for water. The value of h_B for water generally lies between 2,000 and 3,000 (B.Th.U./hr/sq. ft./^{o}F.). For toluene under natural-circulation, the values of h_B are generally between 450 and 630, whereas for ethyl alcohol they lie mostly between 300 and 450. For the forced circulation runs, however, the film coefficients for toluene are lower than those for ethyl alcohol for similar liquid velocities. Attempts at correlating the data on the forced-circulation runs for water, 95.6% ethyl alcohol and toluene, with an equation of the Dittus-Boelter type have failed. The boiling film coefficients correspond to liquid velocities of from 5 to 15 ft/sec., on the basis of the forced-circulation results.

The coefficients in the boiling section increase with Δt_B (Ch. I.). With increasing feed rate they decrease to a greater or lesser degree, depending upon the liquid, and then increase again, but this effect is comparatively small.

(6) The boiling of water and 95.6% ethyl alcohol over heated platinum wires has been studied with the liquids under forced-circulation, at liquid velocities of 1 ft/sec., 2 ft/sec., and 2.9 ft/sec., respectively. With water two

wires of 0.02 in. diameter and 0.01 in. dia. have been used while with ethyl alcohol an additional wire of 0.005 in. diameter has also been used. Test sections of about 6.8 in., with potential leads at about 1½ in. from each end of the wires, have been used. Most of the work is confined to the nucleate region [illegible] although two series of tests on ethyl alcohol also include results on the film region. The curves in the nucleate and film regions are of the same form as generally accepted. They are, however, placed higher in the natural-convection and lower nucleate boiling regions, due to the effect of turbulence caused by forced-circulation. Curves for water are higher than for ethyl alcohol, and those for thinner wires are placed higher than the curves for the thicker wires, for temperature drops up to about 25°F. Above this value of temperature drop velocity and wire diameter hardly seem to have any great effect on the position of the curve, within limits of experimental error.

(7) Latent heat determinations have been made on 95.6% ethyl alcohol, and high purity toluene at atmospheric and lower pressures, using an electrical apparatus. Boiling Point vs. Pressure and Latent Heat vs. Boiling Point curves have been obtained for the two liquids.

SUGGESTIONS FOR FURTHER WORK.

The following suggestions are offered for extending the present investigations:-

(1) More work is needed to elucidate factors affecting the origin of a bubble. What, for example, is the nature of the nuclei and what decides whether a particular spot on an otherwise uniform surface will become an active nucleus? It has been observed that as the temperature of the hot surface increases the number of active nuclei also increases. When the temperature is lowered again, the nucleus which became active first is also the last to cease to be active. This would suggest that temperature has a marked influence in activating a particular nucleus, and that some nuclei need a higher temperature than others to become active. The formation of bubbles in supersaturated solutions of gases in liquids might be correlated with this nuclear boiling. For example, the same ebullator could be tried both with the superheated liquids and with the supersaturated gas solutions. For these investigations advantage could be taken of the methods employed by Dean[32], Larson[10], and Wismer & his associates[28,29].

(2) An electrically heated vertical tube evaporator could be designed. This would eliminate all the resistance

on the "steam side". The only resistance in such a set-up would be the liquid film on the inside. For temperature measurements, tube wall and travelling thermocouples could be used. Such a set-up would permit a wide variation in temperature drops and heat loads, and a great accuracy could be attained. Much work is needed to elucidate the exact operation of temperature drop, viscosity, surface tension, and nature of the liquid, etc.

(3) Some of the results reported here depend upon temperature measurements in the non-boiling section. There is some doubt as to the accuracy of these measurements. It would be of interest if the distribution of temperature across the tube could be explored by a thermocouple moving across instead of up and down.

(4) For boiling liquids in forced-circulation parallel to heated wire, the effects of the nature of the liquid, surface active agents, and the nature of the wire surface itself, could be studied. The wire surface could be coated with a thin film of finely-divided platinum, for example, and the nature of boiling and that of the boiling curve observed. Wires of pure platinum could be used to check the accuracy of the present results. Wires of other metals could be also used. With the present set-up high velocities

of circulation could not be attained. A rotary pump could be used in the circulationg system for obtaining high fluid velocities. Work could be extended to pressures above and below atmospheric.

.....
...

TABLE OF UNITS AND NOMENCLATURE.

A = Heat Transfer Area; for vertical tube evaporators computed on the basis of the average of internal and external diameters; sq. ft.

C = Sp. Heat, B.Th.U./(lb.)(^{o}F).

D = Diameter, Ft.

E = Voltage or Potential Drop, Volts.

h = Film Coefficient of Heat Transfer, B.Th.U/hr/sq.ft/^{o}F.

h_B = " " " " " for Boiling Section.

h_{NB} = " " " " " " Non-boiling "

h_h = " " " " " " for Heating Water.

h_w = " " " " " " " Tube Wall.

k = Thermal Conductivity, B.Th.U/hr/sq.ft/(^{o}F per ft.).

Q = Total Heat Load in a given time, B.Th.U.

q = " " " per hour, B.Th.U/hr.

q/A = Heat Flux, B.Th.U/hr./sq.ft.

q_B = Heat Load per Hour through the Boiling Section, B.Th.U/hr.

q_{NB} = " " " " " " Non-Boiling Section, B.Th.U/hr.

U = Overall Heat Transfer Coefficient, based on the Length Mean Temperature Drop, Δt_m, for the entire tube, B.Th.U/hr/sq.ft/^{o}F.

U_B = Overall Heat Transfer Coefficient for the Boiling Section.

U_{NB} = Overall " " " " " Non-Boiling section.

TABLE OF UNITS AND NOMENCLATURE. (Continued)

V = Velocity, Ft./sec.

Δt = Temperature Drop, $^{o}F.$

Δt_A = Apparent Temperature Drop from Heating Side to the Separator.

Δt_B = Temp. Drop for the Boiling Section.

Δt_{NB} = " " " " Non-Boiling Section.

Δt_m = Length Mean Temp. Drop for the entire tube.

μ = Absolute Viscosity;

Viscosity in centipoises x 0.000672
= Viscosity in lbs./(sec.)(ft.)

Viscosity in Centipoises x 2,42
= Viscosity in lbs./(hr.)(ft.).

ρ = Density, lbs./cu.ft.

List of References.

1. Sauer, Cooper, Akin and MaAdams, Mech. Engg., 60, 669, (1938).
2. Drew and Mueller, Trans. Am. Inst. Chem. Engrs., 33, 449, (1937).
3. McAdams, "HEAT TRANSMISSION", Second Edition, 1942, (McGraw-Hill Book Co., Inc.).
4. Akin and McAdams, Trans. Am. Inst. Chem. Engrs., 35, 137 (1939).
5. Rhodes and Bridges, Trans. Am. Inst. Chem. Engrs. 35, 73 (1939).
6. McAdams, Addoms, Rinaldo and Day, Chem. Engg. Progress, 44, 639 (1948).
7. Farber and Scorah, Trans. Am. Soc. Mech. Engrs., 70, 369 (1948); cited by Skaperdas, Ind. & Eng. Chem., 41, No. 1, Jan., 1949, in the Section dealing with Heat Transfer, of the Chapter on Unit Operations.
8. Baulk, J. Brit. Coal Util. Res. Assn., 9, No. 6 (June, 1947).
9. Jakob, Trans. Am. Inst. Mech. Engrs., 58, 643 (1936).
10. Larson, Ind. Eng. Chem., 37, 1004 (1945).
11. Maxwell, " Theory of Heat ", p. 291, (Longmans Green & Co., 1894).
12. Reynolds, "Scientific Papers", Vol. I, p. 231 (1900), cited by Ref. 10.
13. Worthington, Trans. Roy. Soc. (London), A 183, 355 (1892); cited by Ref. 10.
14. Young, "Natural Philosophy", Vol. 1, p. 473 (1807); cited by Ref. 10.
15. Philipp & Tiffany, Refrig. Eng., 25, 140 (March, 1933).
16. Insinger and Bliss, Trans. Am. Inst. Chem. Engrs., 36, 491 (1940).
17. Barns, Phil. Mag., [5] 38, 34 (1894).
18. Callendar, Proc. Inst. Mech. Engrs., (London), 53, 1915.
19. Goodenough, Power, 66, 466 (1927).
20. Keenan, "Thermodynamics", pp. 431, 435; John Wiley & Sons, 1941.
21. Wilson, Trans. Roy. Soc., (London), A 188, 265 (1897).
22. Yellott, Trans. Am. Soc. Mech. Engrs., 56, 44 (1934).
23. Iterson, Engineering, 142, 95 (1936).
24. Findlay and King, J. Chem. Soc., 105, 1297 (1914).
25. " " Williams, J. Chem. Soc., 103, 1170 (1913).
26. Kenrick, Wyatt and Wismer, J. Phys. Chem., 28, 1308, (1924).
27. Eggleton and Kermack, Chemical Products, Vol. 8, No. 11-12, pp. 75-80 (Sept.-Oct., 1945).

28. Kenrick, Wismer and Gilbert, J.Phys.Chem., 28, 1297 (1924).
29. Wismer, J.Phys.Chem., 26, 301 (1922).
30. Furth, Proc.Cam.Phil.Soc., 37, pp. 252, 276,(1941).
31. Dixon, Proc.Roy.Soc., Dublin, NS 14, 229 (1914).
32. Dean, J. Applied Phys., 15, 446 (1944).
33. Adam, N.K., "Physics and Chemistry of Surfaces" , p.146, (Oxford Univ. Press, 1938).
34. Cassel, J. Applied Phys., 15, 792, (1944).
35. Jakoby and Bischmann, Ind.Eng.Chem., 40, 1360, (1948).
36. Foulk and Groves, Ind.Eng.Chem.,25, 800, (1933).
37. Gunderson and Denman, Ind.Eng.Chem., 40, No.8,(Aug., 1948).
38. Pridgeon and Badger, Ind.Eng.Chem., 16, 474-478 (1924).
39. Bonilla and Perry, Trans.Am.Inst.Chem.Engrs., 37, 685, (1941).
40. Cryder and Finalborgo, Trans.Am.Inst.Chem.Engrs., 33, 346, (1937).
41. Cichelli and Bonilla, Trans.Am.Inst.Chem.Engrs., 41, 755, (1946).
42. Bonilla and Eisenberg, Ind.Eng.Chem., 40, 1112, (1948).
43. Foust, Baker and Badger, Trans.Am.Inst.Chem.Engrs., 35, 45, (1939).
44. Brooks and Badger, Trans. Am.Inst.Chem.Engrs., 33, 392, (1937); Ind.Eng.Chem., 29, 918, (1937).
45. Stroebe, Baker and Badger, Trans.Am.Inst.Chem.Engrs., 35, 17, (1939); Ind.Eng.Chem., 31, 200, (1939).
46. Boarts, Badger and Meisenburg, Trans.Am.Inst.Chem.Engrs., 33, 363, (1937); Ind.Eng.Chem., 29, 912, (1937).
47. Coates and Badger, Trans.Am.Inst.Chem.Engrs., 32, 49, (1936).
48. Badger, Monrad and Diamond, Ind.Eng.Chem., 22, 700, (1930).
49. Cessna, Lientz and Badger, Trans.Am.Inst.Chem.Engrs., 36, 759, (1940).
50. Cessna and Badger, Trans.Am.Inst.Chem.Engrs., 37, 311, (1941).
51. Badger and Shepard, Trans.Am.Inst.Chem.Engrs., 13, Part I, 101, (1920).
52. Logan, Fragen and Badger, Ind.Eng.Chem., 26, 1044, (1934).
53. Linden and Montillon, Trans.Am.Inst.Chem.Engrs., 24, 120, (1930).
54. Cryder and Gilliland, Ind.Eng.Chem., 24, 1382, (1932).
55. Oliver, cited by Ref. 3, Page 323.
56. McAdams, Woods and Bryan, Trans.Am.Soc.Mech.Engrs., 63, 545, (1941).
57. Badger, Trans.Am.Inst.Chem.Engrs., 13, Part II, 139, (1920).
58. Moore, Trans.Am.Inst.Chem.Engrs., 15, Part. II, 233, (1923).
59. Rumford, J.Soc.Chem.Ind., 66, No.9, 309-312 (Sept., 1947).

60. Hagenmacher, Ind.Eng.Chem., 40, 436, (1948).
61. Tyrer, J.Chem.Soc., 99, Part II, 1633, (1911).
62. Brown, J.Chem.Soc., 83, Part I, 987, (1903).
63. Marshall and Ramsay, Phil.Mag., 41, 38, (1998).
64. Fiock, Ginnings and Holton, J.Res.Nat.Bur.St., 6, 881, (May, 1931).
65. Willingham, Taylor, Pignocco and Rossini, ibid., 35, 219, (Sept., 1945).
66. Matthews, Ramsdell and Thompson, J.Am.Chem.Soc., 48, 562, (1926).
67. Perry, " CHEMICAL ENGINEERS' HANDBOOK ", McGraw-Hill Book Co., Inc., Sec.Ed., 1941.

****